ION RETENTION AND MOVEMENT

IN SOILS WITH VARIABLE CHARGE COLLOIDS

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ABSTRACT

An experiment was designed to study distribution of ions in leachate, plant and soil as a function of phosphate and silicate application. Two soils containing variable charge colloids were used. Application of phosphorus and silicon reduced cation leaching. In one soil 50 percent of the calcium could not be accounted for in the leachate and plant or in N-NH_4OAc extract. This calcium was "fixed" as specifically adsorbed ion on the colloid surface. Specifically adsorbed calcium resulted in a lowering of cation exchange capacity in one soil treated with 750 ppm phosphorus. A simple linear model for variable charge colloids was used to explain the experimental results.

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INTRODUCTION

Soils contain colloids of either the constant charge or variable charge type or more likely, mixtures of both types.

The relation between the surface charge σ, and surface potential ϕ_o is

$$\sigma = \frac{Dk}{4\pi} \phi_o$$

where D is the dielectric constant of water and k is the reciprocal of the double layer thickness. This limiting relationship holds only for low surface potentials, but is presented in this form because of its simplicity.

In a constant charge system manipulation of k by alteration of solute concentration results in a change in the surface potential. Montmorillonites and vermiculites are examples of soil colloids which behave in this fashion.

When the solute concentration is changed in a system containing variable charge colloids, the surface charge or potential is altered. Examples of variable charge colloids (sometimes called constant potential colloids) commonly found in soils are the oxides and hydrous oxides of silicon, aluminum and iron. Many of the non-crystalline alumino-silicates also behave like variable charge colloids.

In the agricultural sciences and particularly in soil science, variable charge colloids have more commonly been called colloids with pH dependent charge. This term is an

unfortunate one since it neglects the fact that ions other than H^+ and OH^- can cause surface charge to vary.

It is known that adsorption of anions as $PO_4^{\equiv}$, $SiO_4^{=}$, $SO_4^{=}$ and F^- can alter surface charge on colloids of the variable charge type.

Mekaru (1969) was the first to suggest that the variable charge model might be more appropriate for the high oxide soils of Hawaii. He showed that some soil colloids were in fact positively charged and further that this charge could be reversed by altering the hydrogen ion concentration or by adding ions which are specifically adsorbed on the colloid surface. He was able to increase the cation exchange capacity (CEC) of a soil sample from an initial value of 27 me/100 gm to 128 me/100 gm by adding phosphate to the colloid. Each millimole of phosphate increased CEC by approximately 0.8 me.

Mekaru's work raised some interesting questions. Would the application of phosphate fertilizers or silicate amendments significantly alter the CEC of a soil under normal field practices? One can readily show that one millimole of phosphate per 100 gm of soil is equivalent to about 620 lbs. phosphorus per acre, or one millimole of silicate per 100 gm of soil is equivalent to about 560 lbs. silicon per acre. Would application of these quantities of phosphate or silicate significantly alter the chemistry of soils?

This work was designed to answer three specific questions:

1. Do phosphate and silicate when applied at rates normally used by field agronomists, measurably

increase the CEC of a soil?

2. Does application of phosphate and silicate measurably increase the retention of cations against leaching?
3. What effects would the first two have on the nutrition of plants growing on such a soil?

These three points are in fact the objectives of this thesis. The reader will discover that while these questions will be answered, the answers themselves raise new and more challenging questions.

THEORY AND REVIEW OF LITERATURE

De Bruyn and Agar (1962) are credited by Parks (1967) for combining equation 1,

$$\sigma = \frac{kD}{4\pi} \Phi_o \qquad (1)$$

with equation 2

$$\Phi_o = \frac{RT}{F} \ln \frac{(H^+)}{(H^+)_o} \qquad (2)$$

to arrive at an expression

$$\sigma = \frac{kD}{4\pi} \cdot \frac{RT}{F} \ln \frac{(H^+)}{(H^+)_o} \qquad (3)$$

which shows the relationship between the hydrogen ion concentration of the suspension (H^+) and net surface charge, σ. Other terms in equation 3 are the inverse of the double layer thickness k, dielectric constant D, the gas constant R, the temperature T, the Faraday constant F, and the hydrogen ion concentration at the zero point of charge, $(H^+)_o$. Equation 3 applies only for low surface potential (<25 mv). A more rigorous and non-linear form of this equation should be used when the suspension pH is very different from the zero point of charge.

Equation 3 will predict, at least qualitatively, behavior of soils which contain amorphous colloids or hydrous oxides or oxides of aluminum, iron or silica.

Examples of published data on oxide systems include works

by Parks and de Bruyn (1962), Atkinson etal. (1967) on iron, Yopps and Fuerstenau (1964) on alumina, and Tadros and Lyklema (1968) on silica. Parks (1965, 1967) provides an extensive review on this subject.

The three parameters of equation 3 which can be manipulated for soil management purposes are k, (H^+) and $(H^+)_o$. The double layer thickness 1/k can be altered by altering the ionic strength of the soil solution. The pH of the soil solution (H^+) is routinely controlled by addition of soil amendments. However, unlike soils which contain constant charge colloids, addition of common amendments does more than alter solution pH in soils with variable charge colloids. Sulfate from sulfur, silicate from $CaSiO_3$ or bicarbonate or carbonate from $CaCO_3$ can, by adsorption in the inner Helmholtz layer of the colloid, shift the zero point of charge. Anion adsorption shifts the zero point of charge to lower pH values and thus increases the net negative charge on the colloid. The practical implication of this is that cation retention in soils is greatly increased when anions are specifically adsorbed. Evidence that this is a real and important phenomenon in some soils is found in the works of Ayers and Hagihara (1953) and Mekaru and Uehara (1972). One of the best recent evidence in support of this is found in the appendix of a dissertation by Kinjo (1970). Kinjo showed that the measured CEC of a soil can vary from about 10 to 200 me per 100 gm depending on whether the anion of the saturating salt was NO_3^-, $H_3C_2O_2^-$, $SO_4^=$ or $PO_4^{\equiv}$.

A review of literature on this subject must make reference to the work of Sante Mattson. Kelly (1943) has reviewed Mattson's work. Understandably, Mattson's work has not been fully exploited. His work can be easily understood if studied and examined in the light of equation 3.

Equation 3, however, applies relatively infrequently for soils in temperate regions where the bulk of soil research has been conducted.

Equation 3 would be most likely to apply in Oxisols, in the suborder Andepts and Tropepts, in Spodosol, particularly in the spodic horizon, in many of the Alfisols and Ultisols of the Tropics, and in Entisols which are primarily quartz in minerology. The minerological designation in the family level of the Soil Taxonomy (SCS staff, 1972) should be useful in helping one decide whether equation 3 applies to a particular soil. It should apply in thixotropic, medial, oxidic, ferritic gibbsitic and possibly in kaolinitic families.

Quite obviously, the best model for most soils is one which properly allocates the constant charge or variable charge model to each component of a mineral mixture.

In soils which consist almost entirely of variable charge colloids, it is often useful to know the sign of the charge. There are two simple methods for determining the sign of the charge.

The first involves the change in soil pH when an amount of indifferent electrolyte (KCl or KNO_3) is added to a soil sus-

pension or paste. Mekaru and Uehara (1972) suggest that the sign of the difference in pH ($\triangle$ pH) in N-KCl and water corresponds to the sign of the electrical charge on the colloid. They cite the work of Parks and de Bruyn (1962) to support the validity of their method.

A second and equally simple method requires the measurement of pH of a suspension in which the solids have settled so that there is a sharp boundary between the clear liquid at the top and the sediment below. The pH is measured first with the reference electrode in the clear liquid and again with the reference electrode in the sediment. If the pH difference between the clear liquid and sediment is a positive value, the sign of the charge is positive. Similarly, a zero or negative value corresponds to the electrical charge on the colloid. This is known as the Pallmann effect and is described in several standard texts of colloid chemistry (eg. Kruyt, vol. I, pp. 185, 1952).

The magnitude and sign of the charge should be useful in helping one explain rheologic, ion exchange, dispersion, ion transport and adsorption characteristic of soils. For example, the excellence of soil structure (rheology) in oxidic tropical soils may be related to the low net charge of their colloids. Rapid leaching of potash or nitrate adsorption in tropical soils, situations which rarely occur in temperate regions, can also be predicted in soils if the sign of the charge is known.

MATERIALS AND METHODS

A. Rationale

The experimental plan consisted of treating two soils with various amounts of phosphorus and silicon and then maintaining a budget of selected mobile elements throughout the experiment. For example, one can assume that initially the total K content of the soil would consist of the exchangeable K plus the quantity added as fertilizer. At the end of the experiment, one would account for this K as:

1. the quantity removed as solute in the leachates,
2. the quantity removed by plants, and
3. the quantity remaining in the soil.

The experiment was designed so that for a given soil, pH and Ca were not variables. In a nutshell, the experiment was designed to study the distribution of ions in soil, plant or leachate as a function of phosphorus and silicon applications and with the assumption that equation 3 applies to the soils selected for this study.

B. Soils

Top soils of the Halii series (Typic Gibbsihumox) from the Island of Kauai and the Waimea series (Typic Eutrandepts) from the Island of Hawaii were selected for study. The Halii soil is high in oxides of aluminum and iron and is low in silica. The Waimea soil differs from

the Halii by having a high non-crystalline alumino-silicate content.

Data on both soils are presented in Table I. In selecting these soils, it was felt that the variable charge model would apply in the Halii and would be less likely to apply in the case of the Waimea.

C. Greenhouse Experiment

1. Experimental design

Three replicates of 2 x 2 x 3 x 2 complete block design in an incomplete factorial arrangement of treatments were laid out in the greenhouse. The treatments consisted of two soils, two calcium phosphate (monobasic) levels, three clacium metasilicate levels and two irrigation rates. The high phosphate treatment was applied only to the high silicate and zero silicate treatments, but the low phosphate treatment was applied to all three levels of silicate. This was done to insure plant growth on all treatments, since plants, particularly in the Halii series, would not grow to maturity without this minimum application of phosphorus.

2. Adjustment of soil pH

Titration curves of each soil were made using calcium carbonate or calcium metasilicate and pH of the soil paste was determined. For the Halii soil, pH was raised from an initial value of 4.6 to pH 6 using a combination of calcium silicate and calcium carbonate.

TABLE I. ANALYSIS OF WAIMEA AND HALII SOILS. (MEANS OF DUPLICATES)

	WAIMEA	HALII
Classification:		
Great Soil Group (Old)	Reddish Prairie	Humic Ferruginous Latosol
Order (New)	Inceptisol	Oxisol
Subgroup (New)	Typic Eutrandepts	Typic Gibbsihumox
Family	Medial, isothermic	Ferritic, isothermic
pH paste	6.0	4.6
Δ pH_{KCL}	-0.51	-0.11
Organic Matter (%)	9.55	10.90
Soil N (%)	0.49	0.34
C:N Ratio	11.3	18.6
Extractable P (ppm)	282	1
Extractable Si (ppm)	1,202	29
Exchangeable K (ppm)	1,900	60
Exchangeable Mg (ppm)	1,058	80
Exchangeable Ca (ppm)	4,500	120
Exchangeable Na (ppm)	94	28
CEC (me/100 gm)	52.64	33.33
B.S. (%)	69.68	3.69
Bulk Density (gm/cc, unpacked)	0.74	0.66

For the Waimea soil, pH was not intentionally altered because it was already at pH 6.0, which is near optimum for plant growth for this soil. However, upon addition of 2,000 (484 ppm Si) and 4,000 ppm (968 ppm Si) of calcium metasilicate, the pH rose to values of 6.2 and 6.3 respectively.

3. Application of ions

Sixty samples consisting of one kilogram of soil per sample on an oven dry basis were used. Calcium metasilicate, calcium phosphate (monobasic) and calcium carbonate were applied together in powder form and thoroughly mixed with the soil (Table II). A blanket application of 250 ppm N as ammonium nitrate for the high phosphate-silicate treatment and as calcium nitrate for the remainder was given along with 10 ppm Zn and 3 ppm Mn as chlorides and 1 ppm B as boric acid to all treatments in 25 cc solution per kilogram sample. The Ca content of each treatment was equalized using calcium chloride.

The treated soils were stored in plastic bags and allowed to equilibrate for 10 days. On the tenth day, they were transfered to 1.5 liter containers, 17.5 cm high and 10.5 cm in diameter, lined with plastic bags. At the bottom of every container, an opening about 3 cm in diameter was made. Out of the opening, about 5 cm of the sealed end of the plastic bag was pulled through and about 0.5 cm of the bottom end

TABLE II. APPLIED AND EXTRACTABLE TRUOG P AND Si, AND EXCHANGEABLE AND APPLIED Na. SODIUM WAS APPLIED AS AN IMPURITY IN $CaSiO_3$

Soil	P (mg/pot)			Si (mg/pot)			Na (mg/pot)		
	Appl.	Extr.	Total	Appl.	Extr.	Total	Appl.	Extr.	Total
	100	282	382	0	1,202	1,202	0	94	94
Waimea	750	282	1,032	484	1,202	1,686	9	94	103
				968	1,202	2,170	18	94	112
	100	1	101	0	29	29	0	28	28
Halii	750	1	751	484	29	513	9	28	37
				968	29	997	18	28	46

was cut. Before the soil was placed into the container, the bottom end was lined with 10 x 10 cm plastic netting and glass wool to prevent soil loss. These pots were placed in the greenhouse in a randomized manner on metal landing mats. Glass jars were placed below each container to collect the leachates.

Fifty ppm magnesium and 250 ppm potassium (soil basis) as chlorides were added to the surface of all soils in the containers in solution form (Table III). Three more days were allowed for equilibration.

4. Planting

Three days after the surface application of magnesium and potassium, five Mini Milo hybrid sorghum seeds (Sorghum vulgare) were planted in each pot. First emergence of seedlings took place on the fourth day. Ten days after sowing, the plants were thinned down to two plants per pot.

5. Irrigation water

Apparent field capacity or more appropriately called 'overnight water retention capacity' was determined in the laboratory by saturating each soil core and allowing the water to drain overnight. The moisture of the soil was then determined. Using identical containers as those in the experiment, the retention capacity of each soil was again determined. The moisture content of the soil was first raised to the retention capacity determined earlier. Then an

TABLE III. APPLIED AND EXCHANGEABLE Ca, K AND Mg, AND APPLIED N AND SOIL N FOR ALL TREATMENTS

Soil		Exchangeable	Applied	Total (mg/pot)
Waimea	Ca	4,500	1,860	6,360
	K	1,900	250	2,150
	Mg	1,058	50	1,108
	N	4,916	250	5,166
Halii	Ca	120	2,986	3,106
	K	60	250	310
	Mg	80	50	130
	N	3,433	250	3,683

additional 100 ml of water were applied. The following day, the leachate volume was measured and the weight of the soil and container was measured. Retention capacity was determined by deducting the weight of container. This process was repeated several times until over 90 per cent of the water applied had leached out. This water retention capacity was used for the first irrigation round. The moisture content for each soil was first raised to its retention capacity before the application of the irrigation water. Two irrigation rates of distilled water were applied every fourth day for the first two applications and every sixth day for the rest of the applications. They were 0.86 and 3.44 cm per application. The first application of irrigation was done on the same day after sowing.

The following day all pots were weighed again to determine the water retention capacity which was to be used for the next round of irrigation. These data were summarized and the means for low and high irrigation for each soil were determined. Thus, for the second irrigation round, there were four retention capacity values. The moisture content of all soils were raised to their respective retention capacities before the second round of irrigation. The same procedure was repeated for the 3rd, 4th, 5th and 6th rounds of irrigation. For the seventh irrigation round, four

values of retention capacity were used for each soil instead of two as was previously used. This retention capacity was very much influenced by channels in the soil created by roots. Since all high phosphate treatments showed good growth and thus more root proliferation, their retention values were generally lower than those with low phosphorus. As a result, within each soil and each irrigation rate, there were two values of retention capacity, one value for each phosphorus level. Finally, in the last (8th) round, every retention capacity value was used before irrigation. The pore volume of the Halii and Waimea was 1,182 and 1,007 cc respectively.

6. Leachate sampling and analysis

A total of eight sets of leachates was collected. Every second set of leachates was composited with the earlier set for every treatment in each replicate. In all, there were four sets of leachate for analysis for a given water application rate.

The composited leachate of a treatment was analyzed for calcium, potassium, magnesium, sodium, phosphorus and silicon. Detailed methods are described in the Appendix.

7. Soil sampling and analysis

After harvest and removal of the roots, the soil samples were stored in plastic bags. CEC of each sample was determined using N-ammonium acetate at pH 7.

Exchangeable calcium, potassium, magnesium and sodium in ammonium acetate were determined. Phosphorus and silicon were extracted from the leached soil using the modified Truog method.

Soil pH's were measured in pastes and 1:5 (soil: water or electrolyte) dilutions prepared with water, N-KCl and N-KNO_3.

Delta pH (Δ pH) of pastes or from 1:5 dilutions defined as follows:

(i) $\Delta pH_{KCl} = pH_{KCl} - pH_{H_2O}$ (paste or 1:5)

(ii) $\Delta pH_{KNO_3} = pH_{KNO_3} - pH_{H_2O}$ (paste or 1:5)

were determined.

8. Plant sampling and analysis

The portion of the plant above the top-most root of the sorghum plant was analyzed. Fresh weight was taken for each pot. All samples were dried in an air draft oven, weighed again and ground in a Wiley Mill.

Each plant sample was analyzed for calcium, potassium, magnesium, sodium, phosphorus and silicon.

Plant parts other than plant tops were defined as roots. They were separated from the soil and washed. Fresh weights and oven dry root weights were recorded.

RESULTS AND DISCUSSION

The simple theory presented earlier in the Theory and Review of Literature section predicts that at a constant soil pH, cation leaching can be reduced if the zero point of charge of a variable charge colloid is shifted to lower pH's. In this case, the zero point of charge was lowered by addition of 100 and 750 ppm P and 484 and 968 ppm Si. The resistance to leaching was measured by applying two (0.86 and 3.44 cm) water application rates. Leachates were collected after each of eight irrigation rounds over a five week period. To ease the work load, leachates I, III, V and VII were combined with leachates II, IV, VI and VIII respectively.

Table IV summarizes the treatments and provides the reader with symbols which will be employed to designate them.

TABLE IV. SUMMARY OF THE TREATMENTS AND SYMBOLS USED FOR LOW WATER APPLICATION RATE (LW) AND HIGH WATER APPLICATION RATE (HW)

ppm Si \ ppm P	100	750
0	LPOSi	HPOSi
484	LPMSi	--
968	LPHSi	HPHSi

A. Leachate

Since the quantity of ions leached from the soil system by water depends not only on the ion retention capacity of the soil but on the interception of these ions by the plant root as well, the experimental results for the leachate are divided into two parts. In the first four leachates (Leachates [I + II] and [III + IV]), it is assumed that the differences in leachate concentration are not influenced by plant uptake because of the small size of the plant. Beyond Leachate IV, one can assume that plant uptake of ionic nutrients may significantly alter the leachate concentration.

Figures 1 and 2 show the effect of P and Si treatments on the composition of leachate for four irrigation treatments. The results clearly demonstrate that addition of Si and P reduces leaching of cations. This difference in the quantity of cations leached increased as the water application rate increased. The amount of P leached from a soil increased with increasing water, P and Si application rates.

The trends are strikingly similar in the Halii and Waimea soils, suggesting that the variable charge model applies equally well in both cases. The dependence of cation retention on applied P and Si is much more pronounced in the Halii. This is most likely related to the fact that Si, P and cations occur in extremely low concentration in

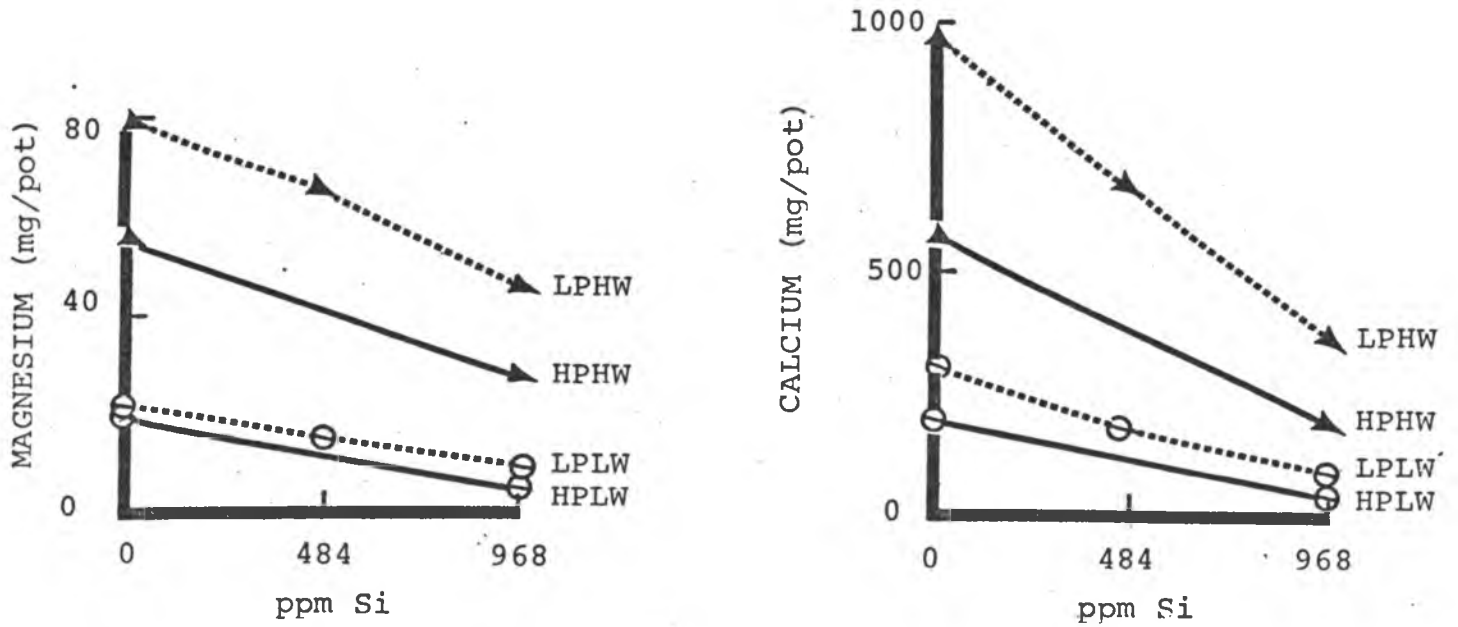

FIGURE 1a. Ca AND Mg IN LEACHATES OF THE HALII SOIL AS A FUNCTION OF Si, P AND IRRIGATION TREATMENTS. LP = 100 ppm P APPLIED, HP = 750 ppm P APPLIED, LW = LOW WATER IRRIGATION AND HW = HIGH WATER IRRIGATION RATE

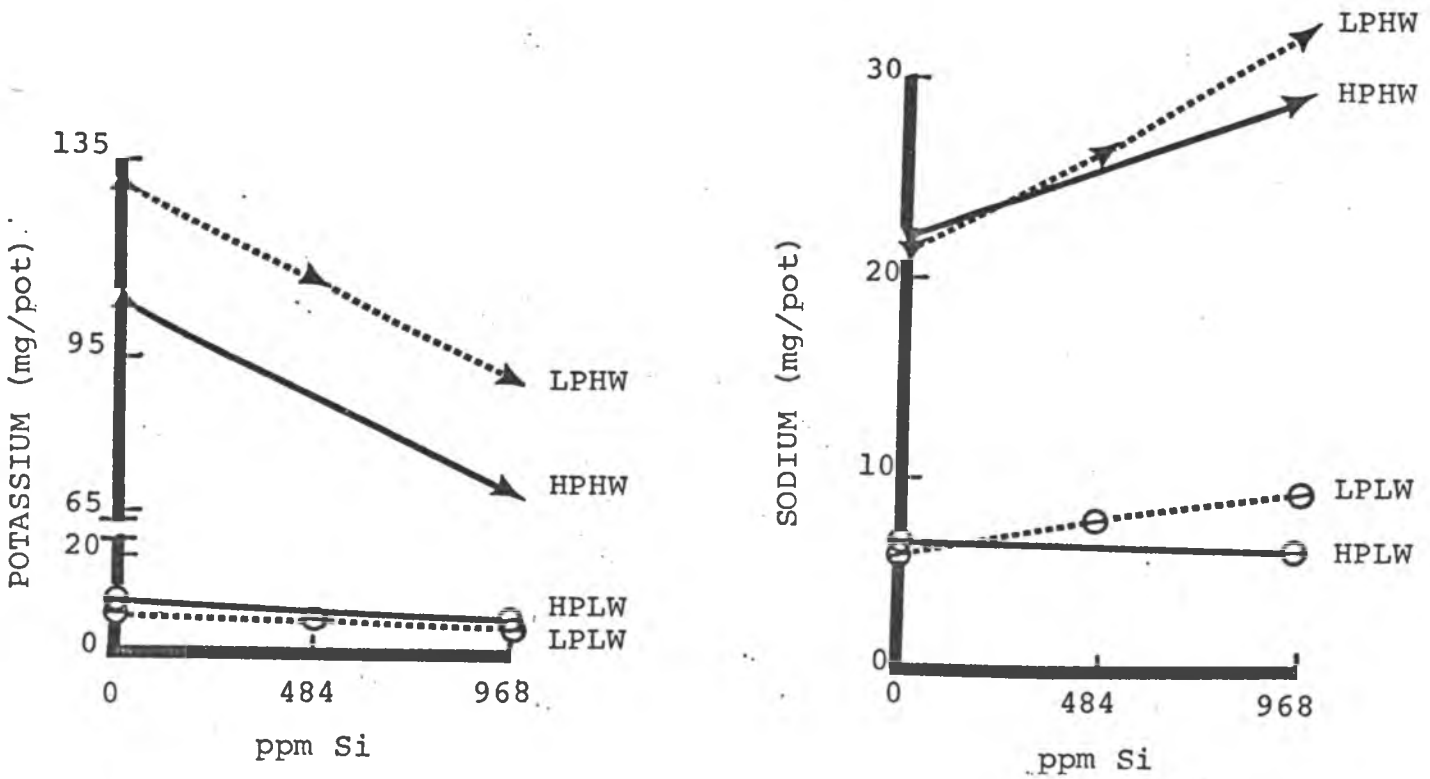

FIGURE 1b. K AND Na IN LEACHATE OF THE HALII SOIL AS A FUNCTION OF Si, P AND IRRIGATION TREATMENTS. LP = 100 ppm P APPLIED, HP = 750 ppm P APPLIED, LW = LOW WATER IRRIGATION RATE AND HW = HIGH WATER IRRIGATION RATE

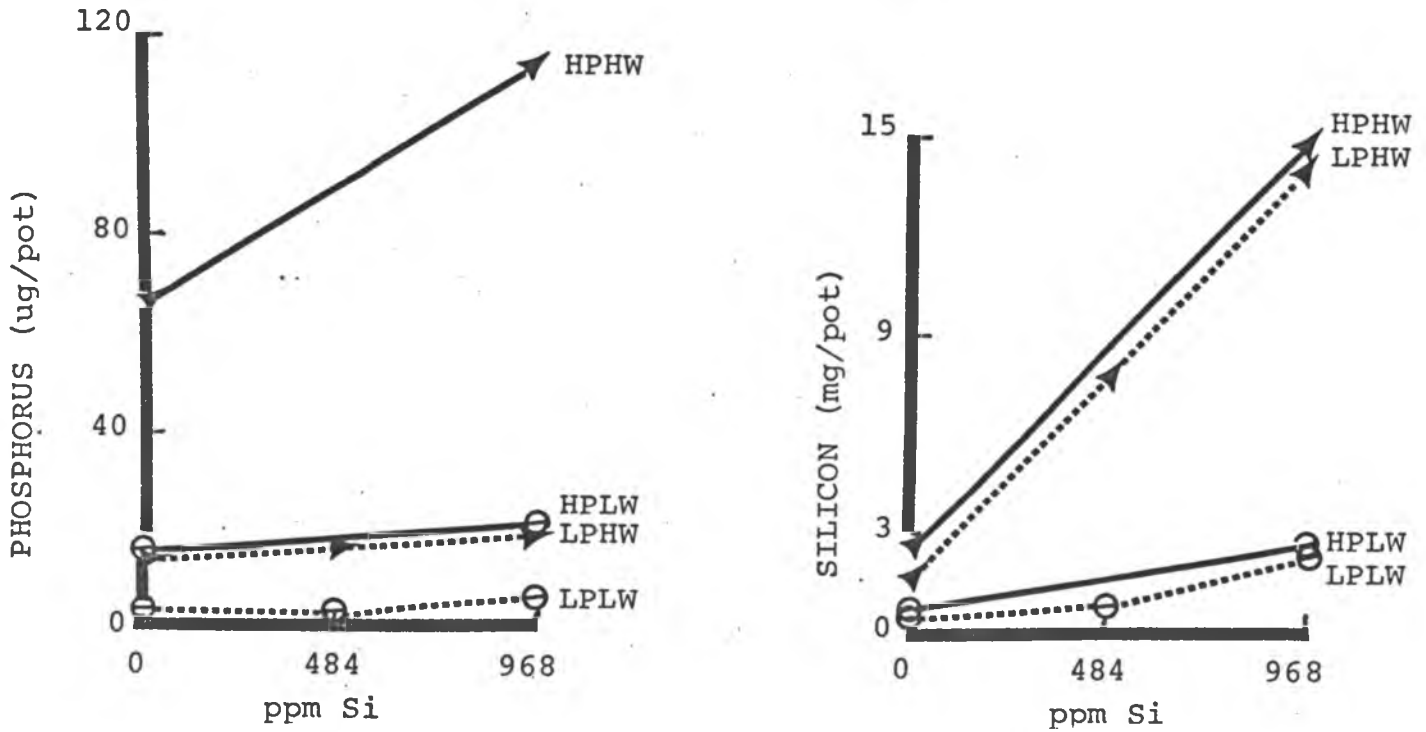

FIGURE 1c. P AND Si IN LEACHATE OF THE HALII SOIL AS A FUNCTION OF Si, P AND IRRIGATION TREATMENTS. LP = 100 ppm P APPLIED, HP = 750 ppm P APPLIED, LW = LOW WATER IRRIGATION RATE AND HW = HIGH WATER IRRIGATION RATE

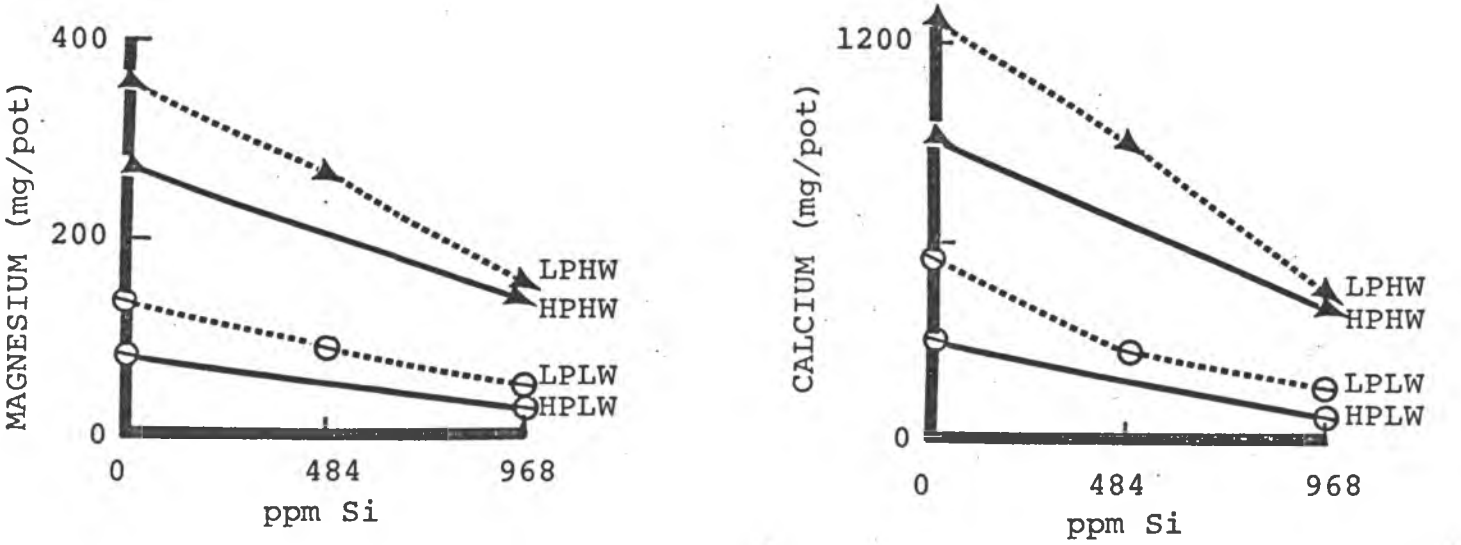

FIGURE 2a. Ca AND Mg LEACHATE OF THE WAIMEA SOIL AS A FUNCTION OF Si, P AND IRRIGATION TREATMENT. LP = 100 ppm P APPLIED, HP = 750 ppm P APPLIED, LW = LOW WATER IRRIGATION RATE AND HW = HIGH WATER IRRIGATION RATE

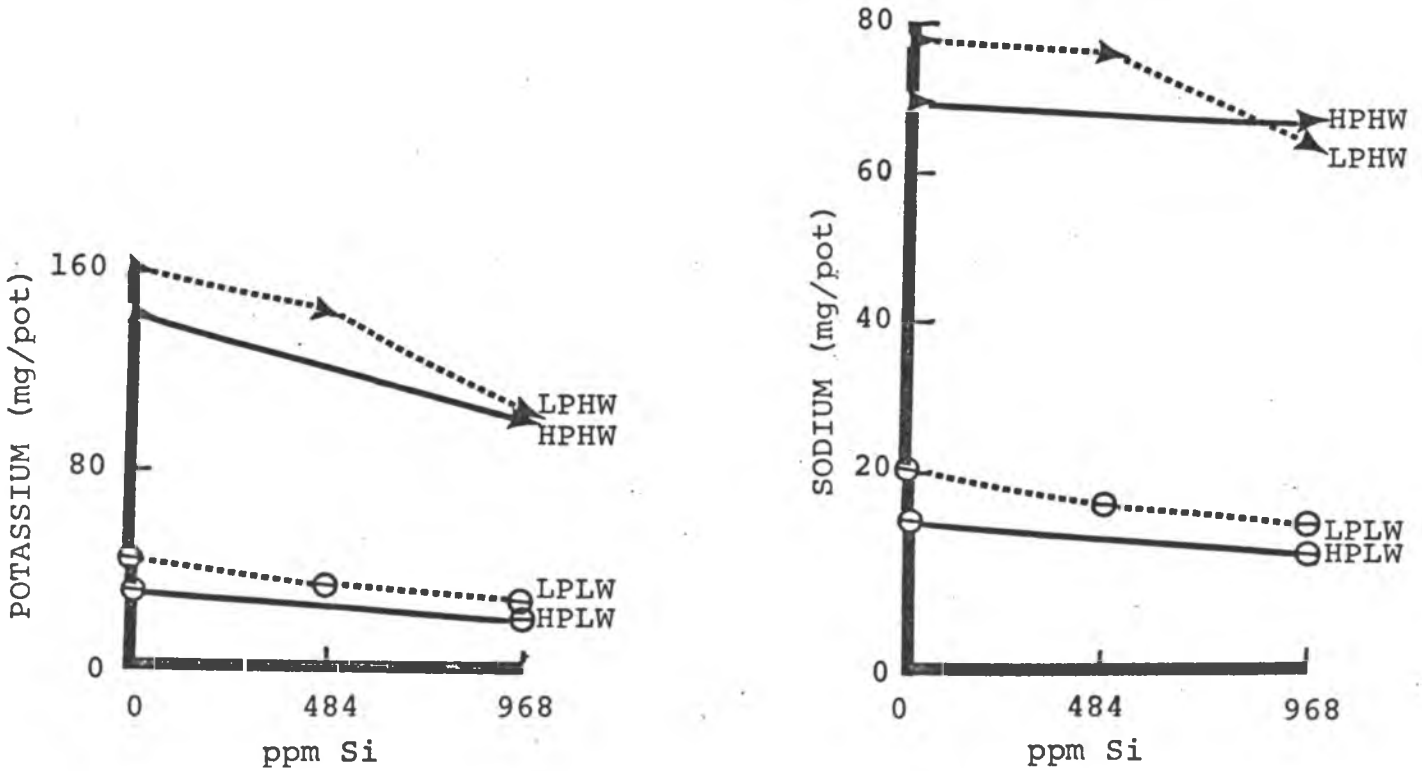

FIGURE 2b. K AND Na LEACHATE OF THE WAIMEA SOIL AS A FUNCTION OF Si, P AND IRRIGATION TREATMENT. LP = 100 ppm P APPLIED, HP = 750 ppm P APPLIED, LW = LOW WATER IRRIGATION RATE AND HW = HIGH WATER IRRIGATION RATE

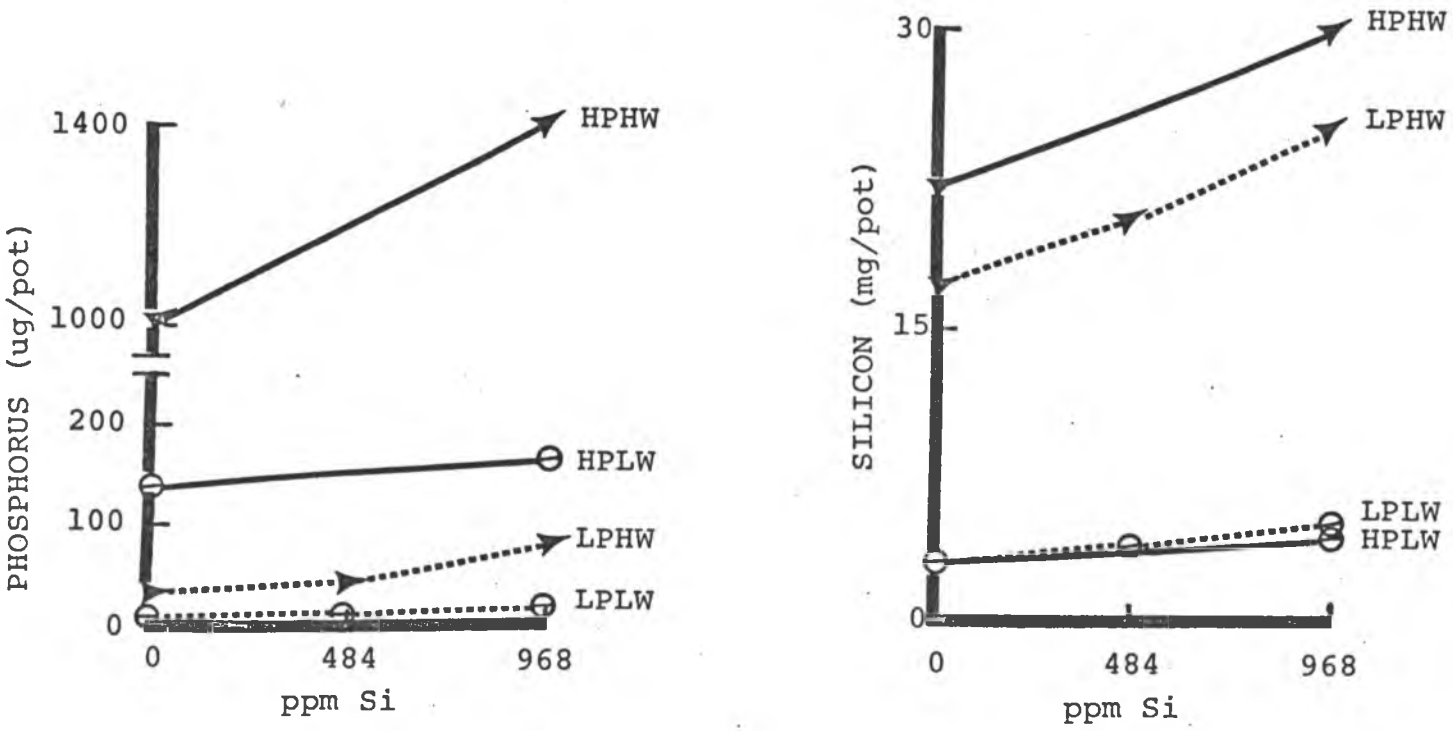

FIGURE 2c. P AND Si LEACHATE OF THE WAIMEA SOIL AS A FUNCTION OF Si, P AND IRRIGATION TREATMENT. LP = 100 ppm P APPLIED, HP = 750 ppm P APPLIED, LW = LOW WATER IRRIGATION RATE AND HW = HIGH WATER IRRIGATION RATE

the Halii compared to the Waimea soil.

When the cummulative loss from each treatment for the entire duration of the experiment is examined (Figures 3 to 14), but now as a function of total volume of leachate collected, it becomes possible to examine much of the same data in a different perspective. The low P-zero Si (LPOSi) treatment releases the largest quantity of cations and the high P-high Si (HPHSi) treatment releases the least. One can now ask whether this difference is related to the greater uptake of ions by the larger and healthier plants growing on the high P-high Si (HPHSi) treatments. This question will be treated in greater detail in a later section, and it is sufficient to note at this point that the greater cation retention of the low P-high Si (LPHSi) treatment relative to the high P-zero Si (HPOSi) treatment is reversed when 1,245 ml of leachate is collected. This occurs for K in the Halii soil, undoubtedly as a result of the greater uptake of K by the larger plants growing in the high P treatments.

An unexpected result of the leaching study is noted when one compares the results of the low leaching rate (below 450 ml) and the high leaching rate (above 450 ml). For a given P and Si treatment, the amount of ions leached from a particular system appears to be single-valued function of the leachate volume and independent of the manner in which water is applied. One would expect the leaching efficiency to be higher in a system in which water was

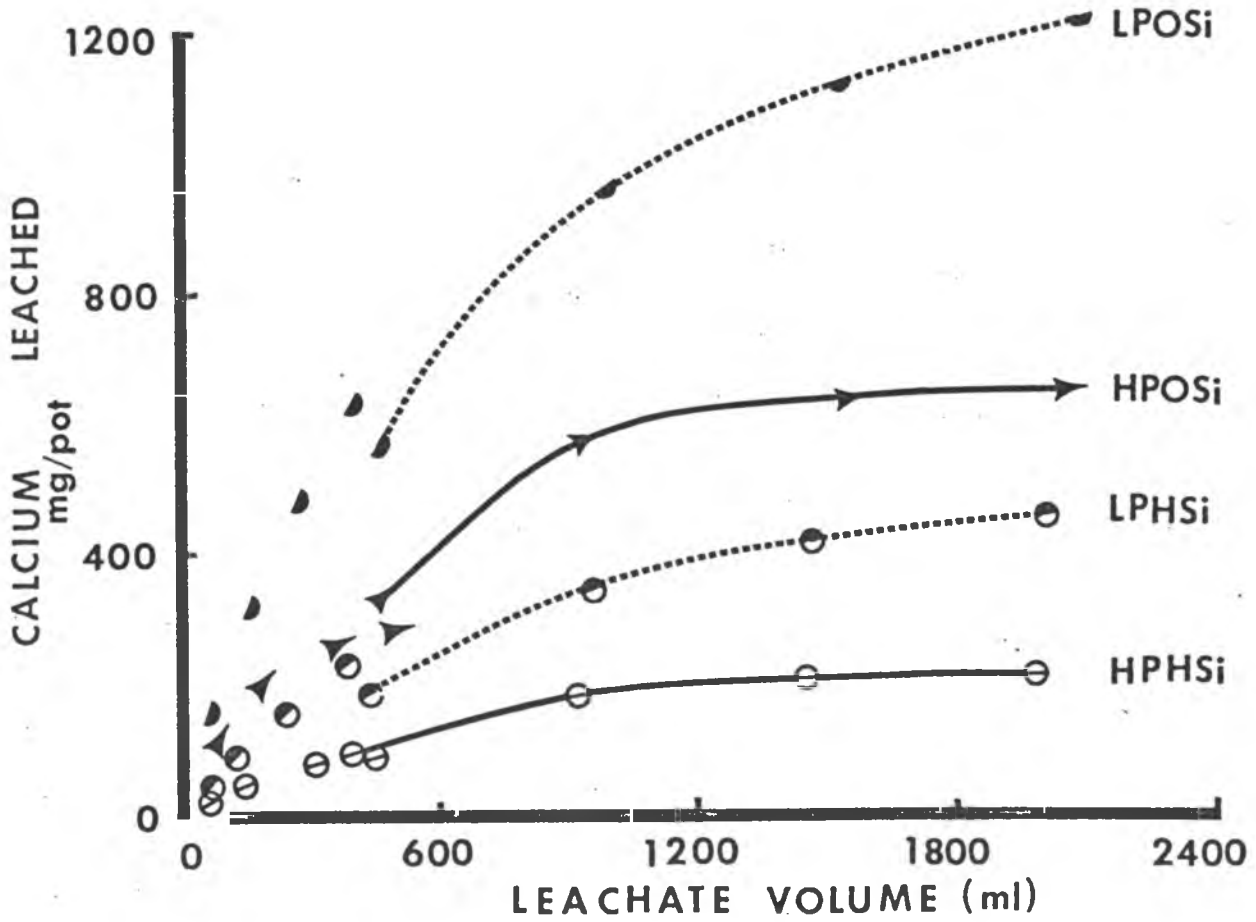

FIGURE 3. CUMMULATIVE Ca LEACHED IN HALII SOIL AS A FUNCTION OF LEACHATE VOLUME. DATA POINTS JOINED BY DASHED OR SOLID LINE REPRESENT LEACHATE FROM HIGH WATER APPLICATION RATE; UNLINED REGION REPRESENTS LOW WATER APPLICATION RATE (LP = 100 ppm P, HP = 750 ppm P, OSi = ZERO Si, AND HSi = 968 ppm Si)

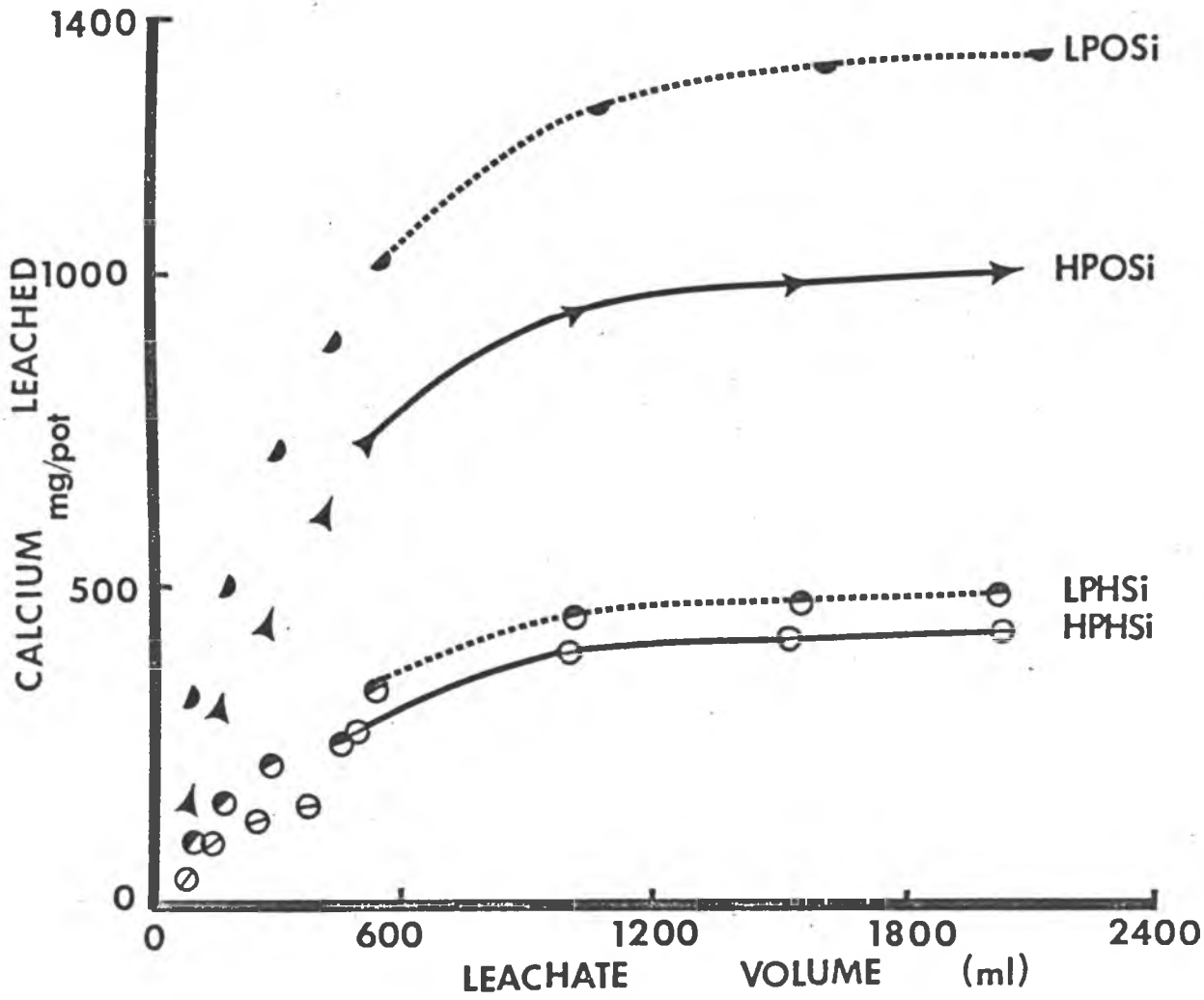

FIGURE 4. CUMMULATIVE Ca LEACHED IN WAIMEA SOIL AS A FUNCTION OF LEACHATE VOLUME. DATA POINTS JOINED BY DASHED OR SOLID LINE REPRESENT LEACHATE FROM HIGH WATER APPLICATION RATE; UNLINED REGION REPRESENTS LOW WATER APPLICATION RATE (LP = 100 ppm P, HP = 750 ppm P, OSi = ZERO Si, AND HSi = 968 ppm Si)

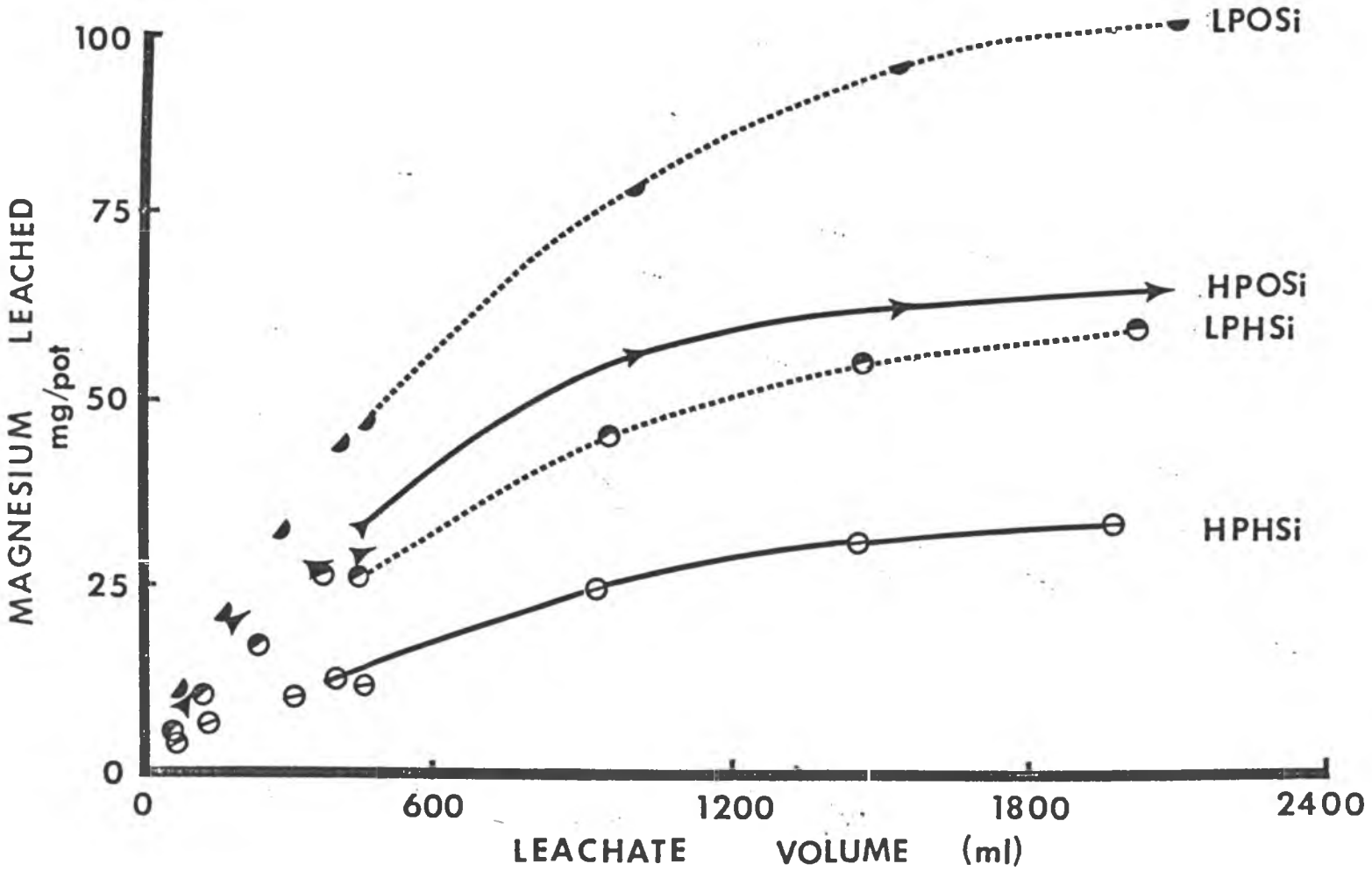

FIGURE 5. CUMMULATIVE Mg LEACHED IN HALII SOIL AS A FUNCTION OF LEACHATE VOLUME. DATA POINTS JOINED BY DASHED OR SOLID LINE REPRESENT LEACHATE FROM HIGH WATER APPLICATION RATE; UNLINED REGION REPRESENTS LOW WATER APPLICATION RATE (LP = 100 ppm P, HP = 750 ppm P, OSi = ZERO Si AND HSi = HIGH Si)

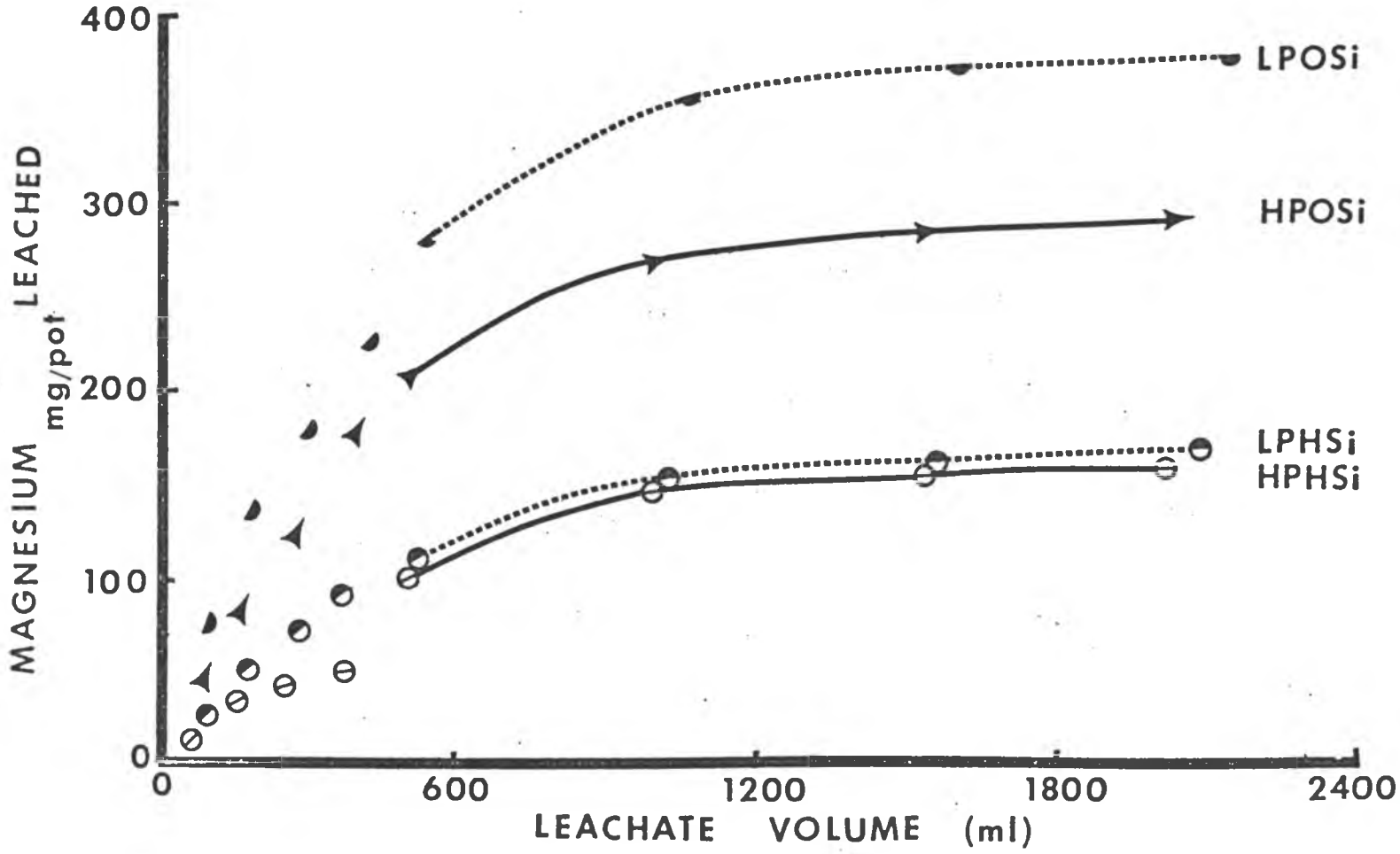

FIGURE 6. CUMMULATIVE Mg LEACHED IN WAIMEA SOIL AS A FUNCTION OF LEACHATE VOLUME. DATA POINTS JOINED BY DASHED OR SOLID LINE REPRESENT LEACHATE FROM HIGH WATER APPLICATION RATE; UNLINED REGION REPRESENTS LOW WATER APPLICATION RATE. (LP = 100 ppm P, HP = 750 ppm P, OSi = ZERO Si AND HSi = 968 ppm Si)

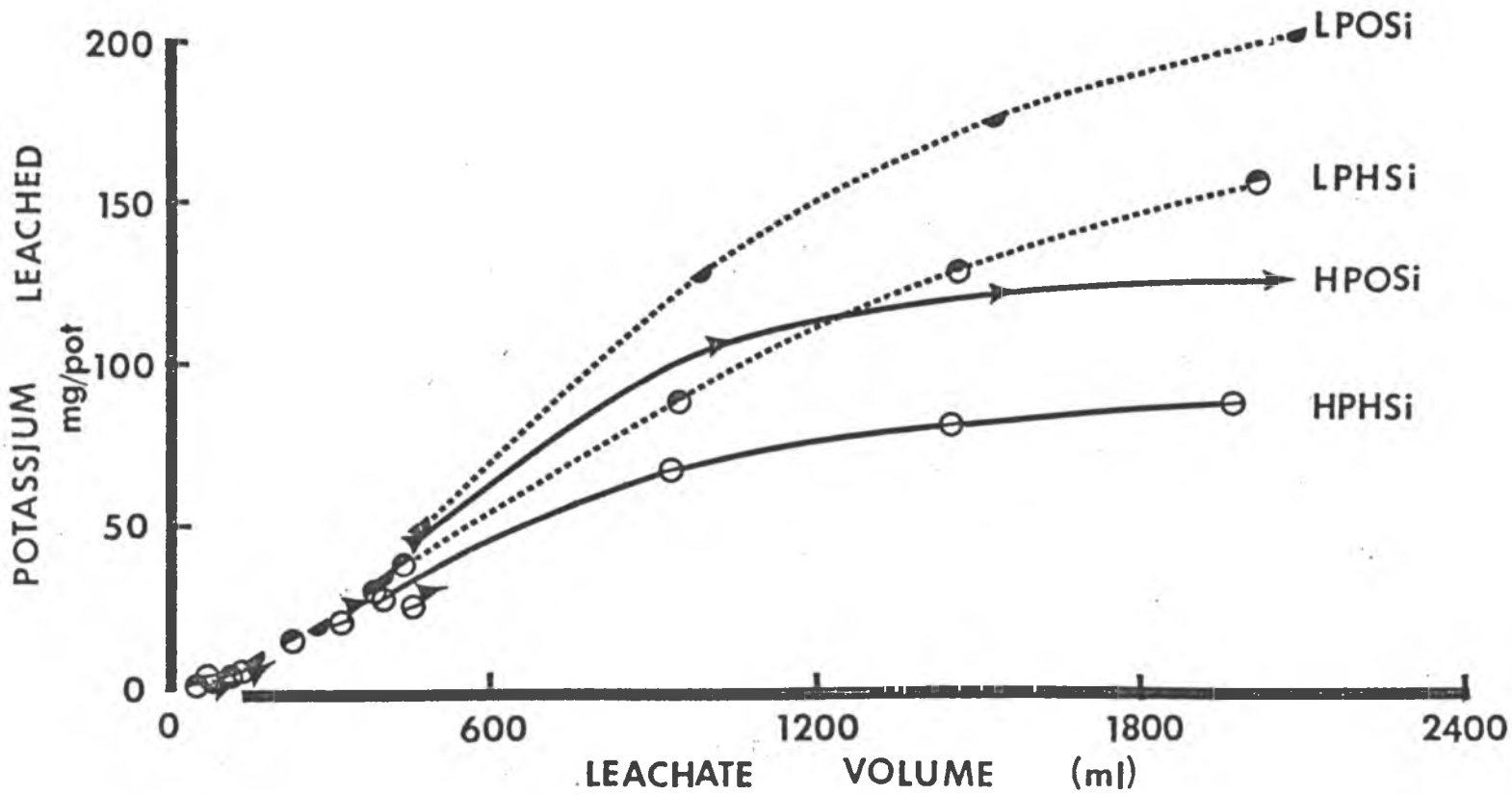

FIGURE 7. CUMMULATIVE K LEACHED IN HALII SOIL AS A FUNCTION OF LEACHATE VOLUME. DATA POINTS JOINED BY DASHED OR SOLID LINE REPRESENT LEACHATE FROM HIGH WATER APPLICATION RATE; UNLINED REGION REPRESENTS LOW WATER APPLICATION RATE (LP = 100 ppm P, HP = 750 ppm P, OSi = ZERO Si, AND HSi = 968 ppm Si)

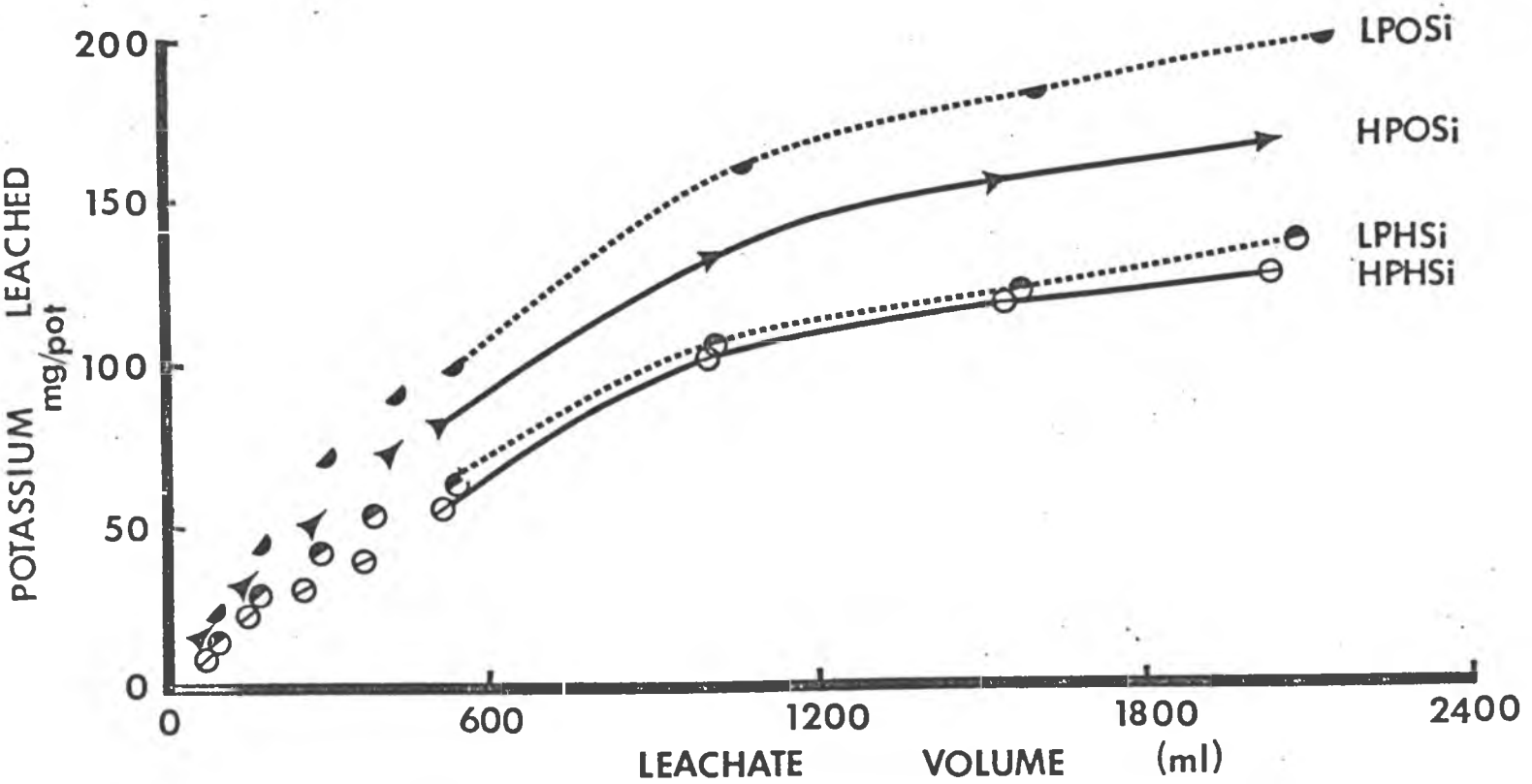

FIGURE 8. CUMMULATIVE K LEACHED IN WAIMEA SOIL AS A FUNCTION OF LEACHATE VOLUME. DATA POINTS JOINED BY DASHED OR SOLID LINE REPRESENT LEACHATE FROM HIGH WATER APPLICATION RATE; UNLINED REGION REPRESENTS LOW WATER APPLICATION RATE (LP = 100 ppm P, HP = 750 ppm P, OSi = ZERO Si, AND HSi = 968 ppm Si)

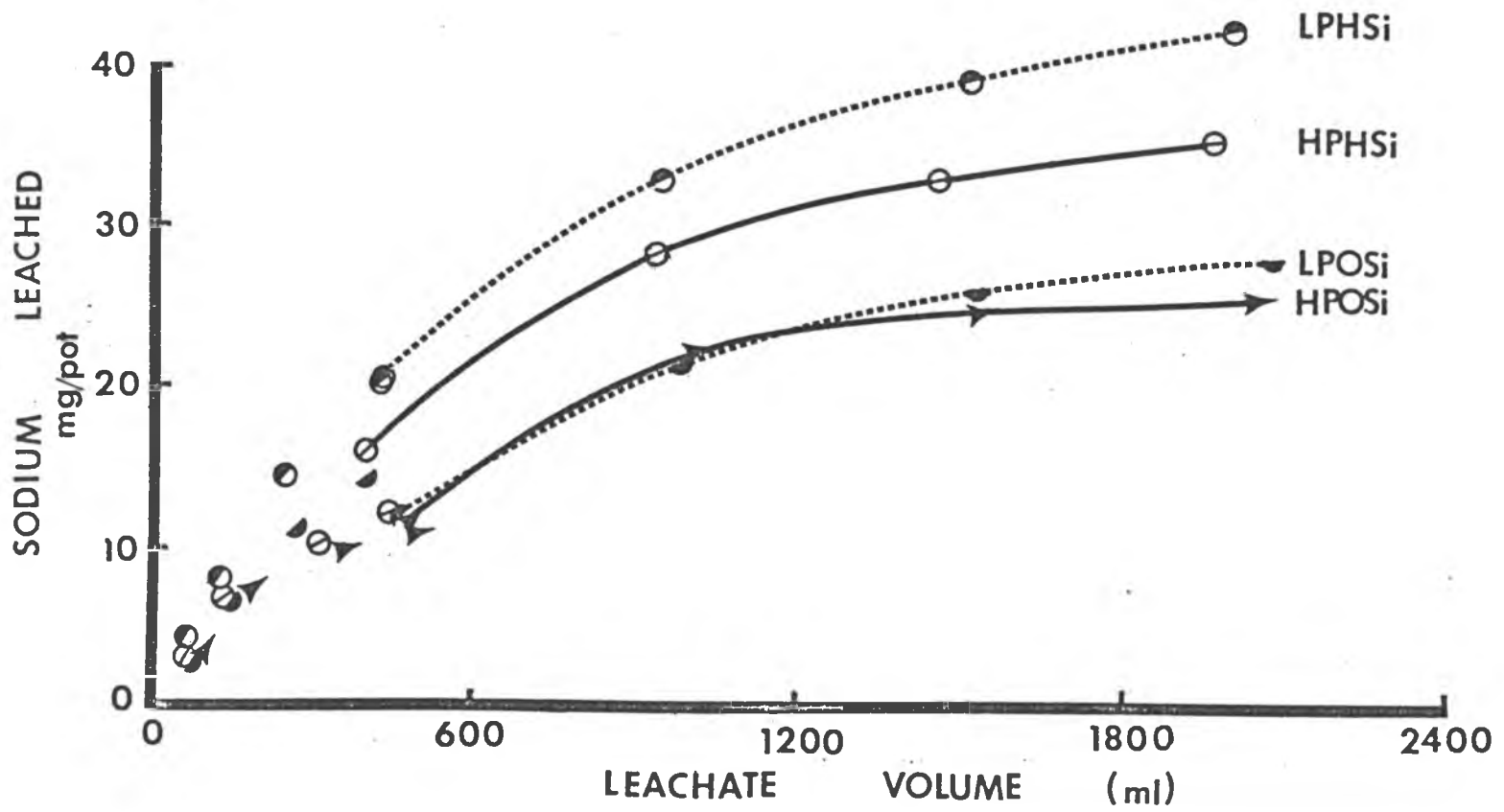

FIGURE 9. CUMMULATIVE Na LEACHED IN HALII SOIL AS A FUNCTION OF LEACHATE VOLUME. DATA POINTS JOINED BY DASHED OR SOLID LINE REPRESENT LEACHATE FROM HIGH WATER APPLICATION RATE; UNLINED REGION REPRESENTS LOW WATER APPLICATION RATE (LP = 100 ppm P, HP = 750 ppm P, OSi = ZERO Si AND HSi = 968 ppm Si)

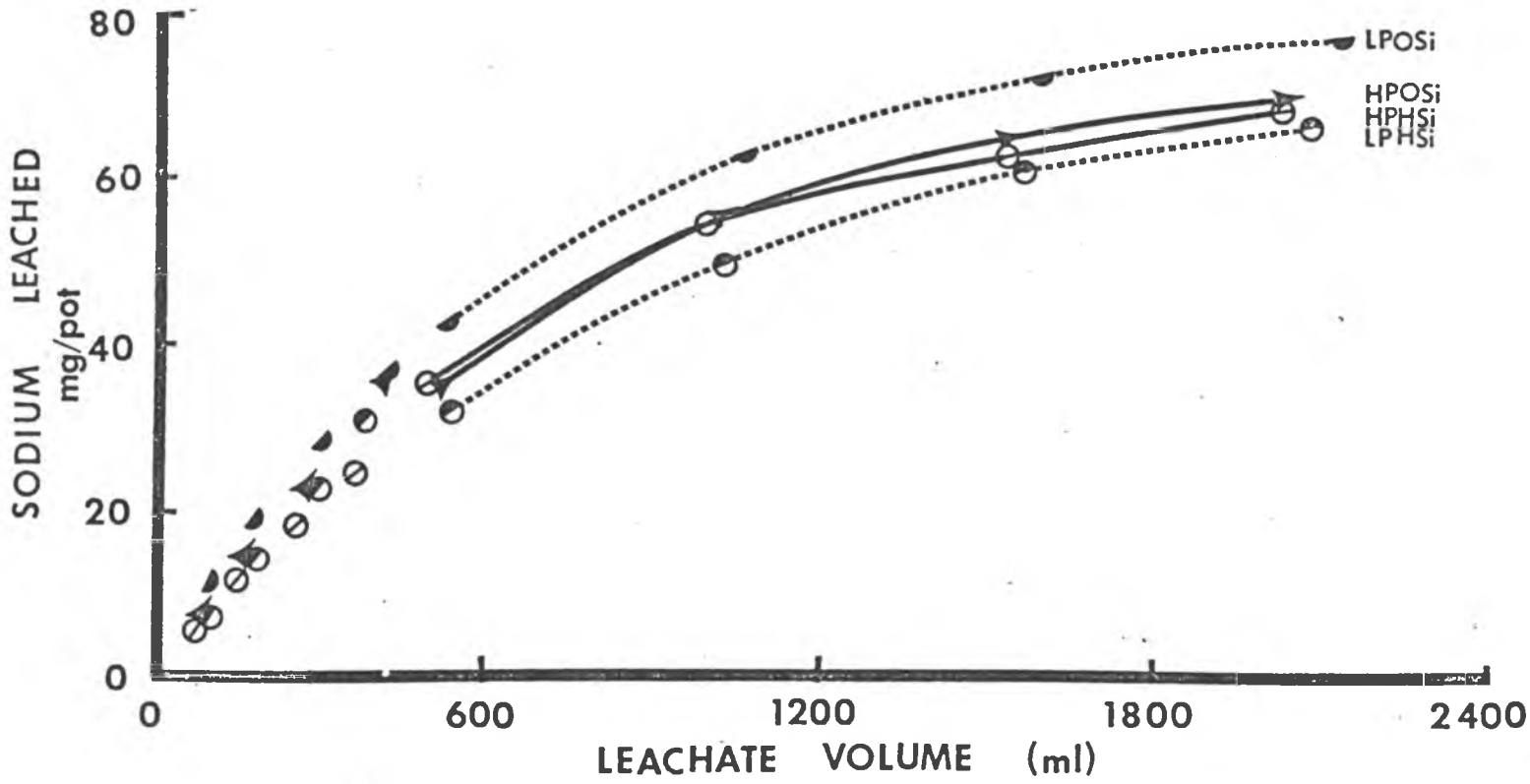

FIGURE 10. CUMMULATIVE Na LEACHED IN WAIMEA SOIL AS A FUNCTION OF LEACHATE VOLUME. DATA POINTS JOINED BY DASHED OR SOLID LINE REPRESENT LEACHATE FROM HIGH WATER APPLICATION RATE; UNLINED REGION REPRESENTS LOW WATER APPLICATION RATE (LP = 100 ppm P, HP = 750 ppm P, OSi = ZERO Si AND HSi = 968 ppm Si)

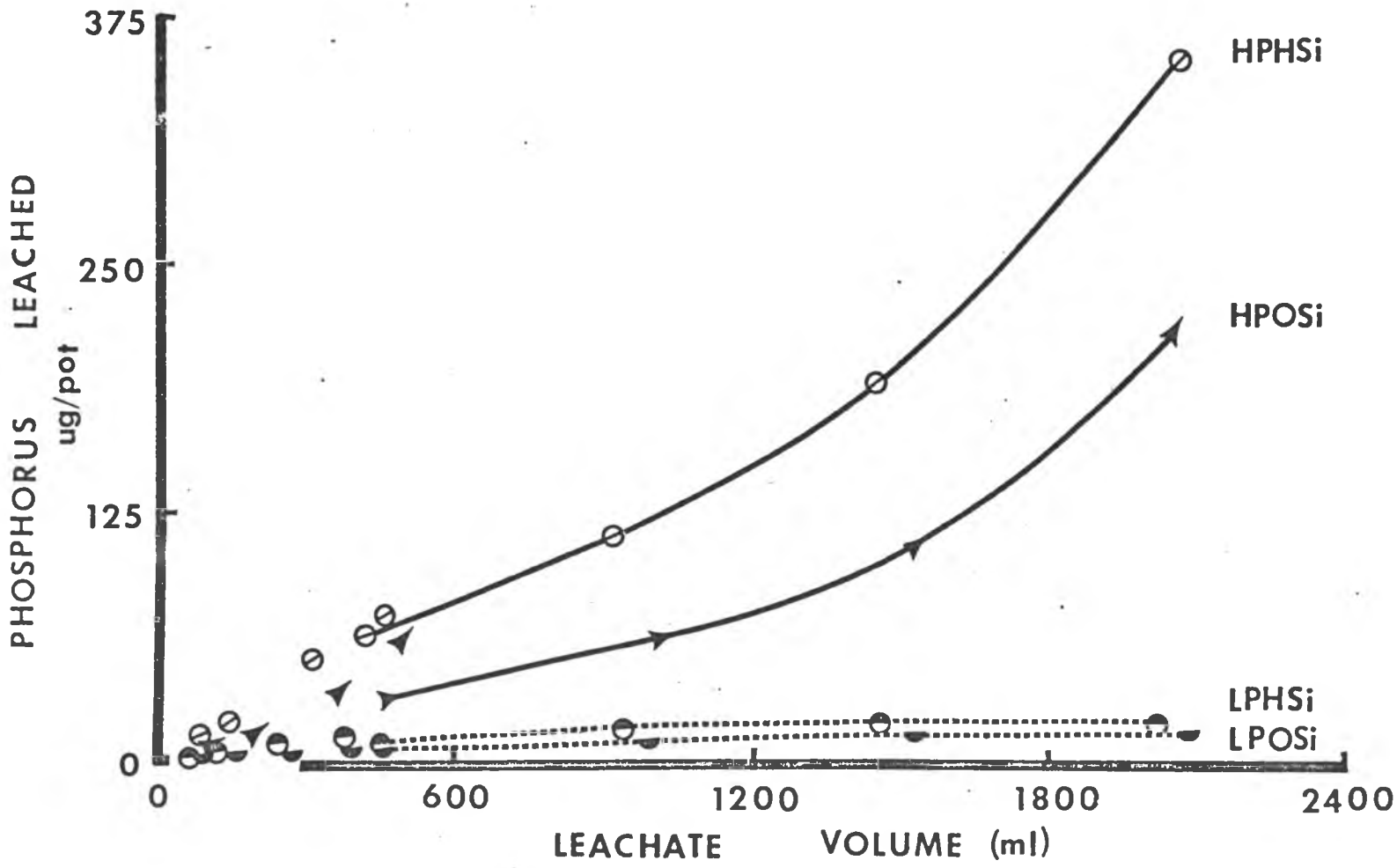

FIGURE 11. CUMMULATIVE P LEACHED IN HALII SOIL AS A FUNCTION OF LEACHATE VOLUME. DATA POINTS JOINED BY DASHED OR SOLID LINE REPRESENT LEACHATE FROM HIGH WATER APPLICATION RATE; UNLINED REGION REPRESENTS LOW WATER APPLICATION RATE (LP = 100 ppm P, HP = 750 ppm P, OSi = ZERO Si AND HSi = 968 ppm Si)

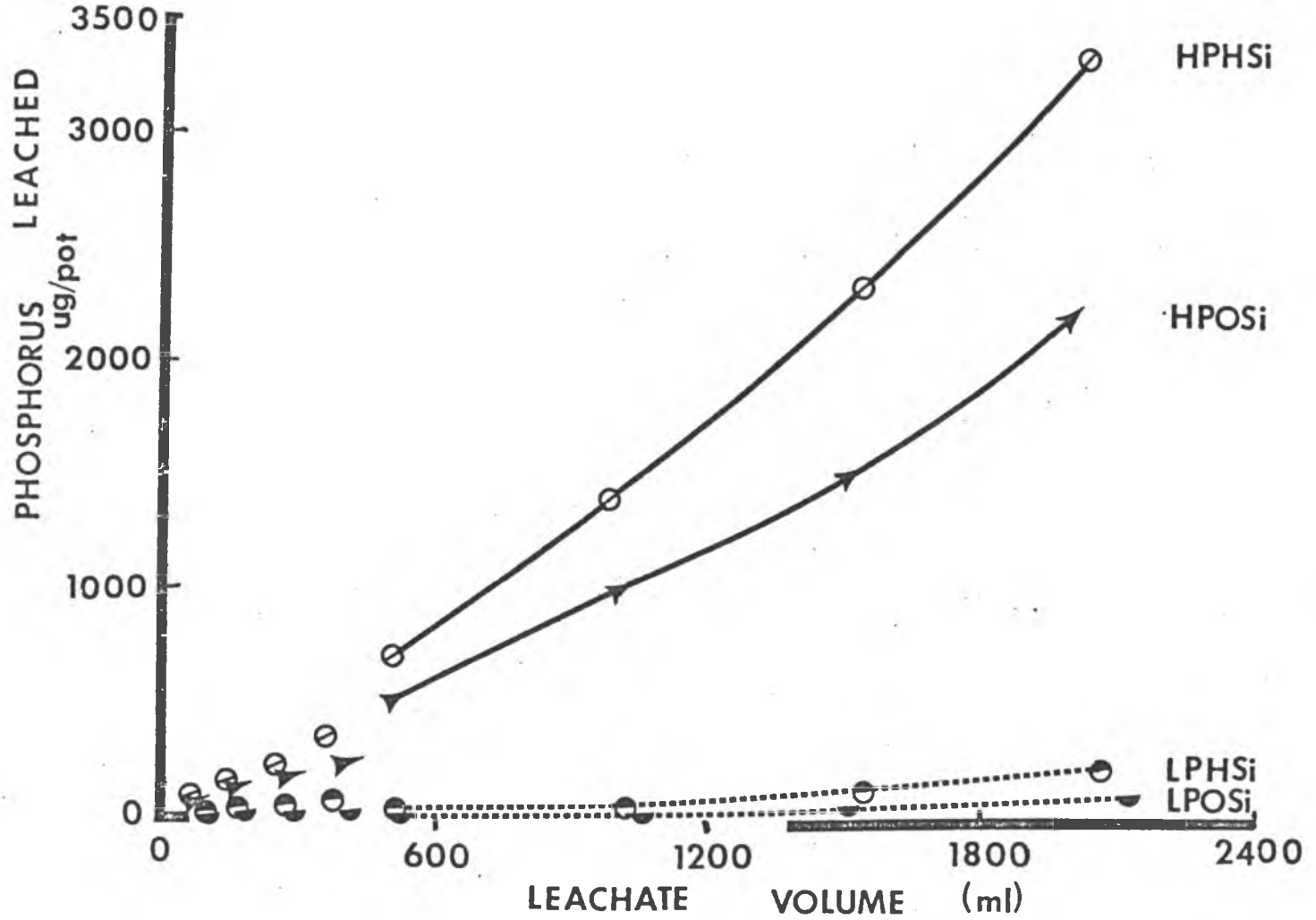

FIGURE 12. CUMMULATIVE P LEACHED IN WAIMEA SOIL AS A FUNCTION OF LEACHATE VOLUME. DATA POINTS JOINED BY DASHED OR SOLID LINE REPRESENT LEACHATE FROM HIGH WATER APPLICATION RATE; UNLINED REGION REPRESENTS LOW WATER APPLICATION RATE (LP = 100 ppm P, HP = 750 ppm P, OSi = ZERO Si AND HSi = 968 ppm Si)

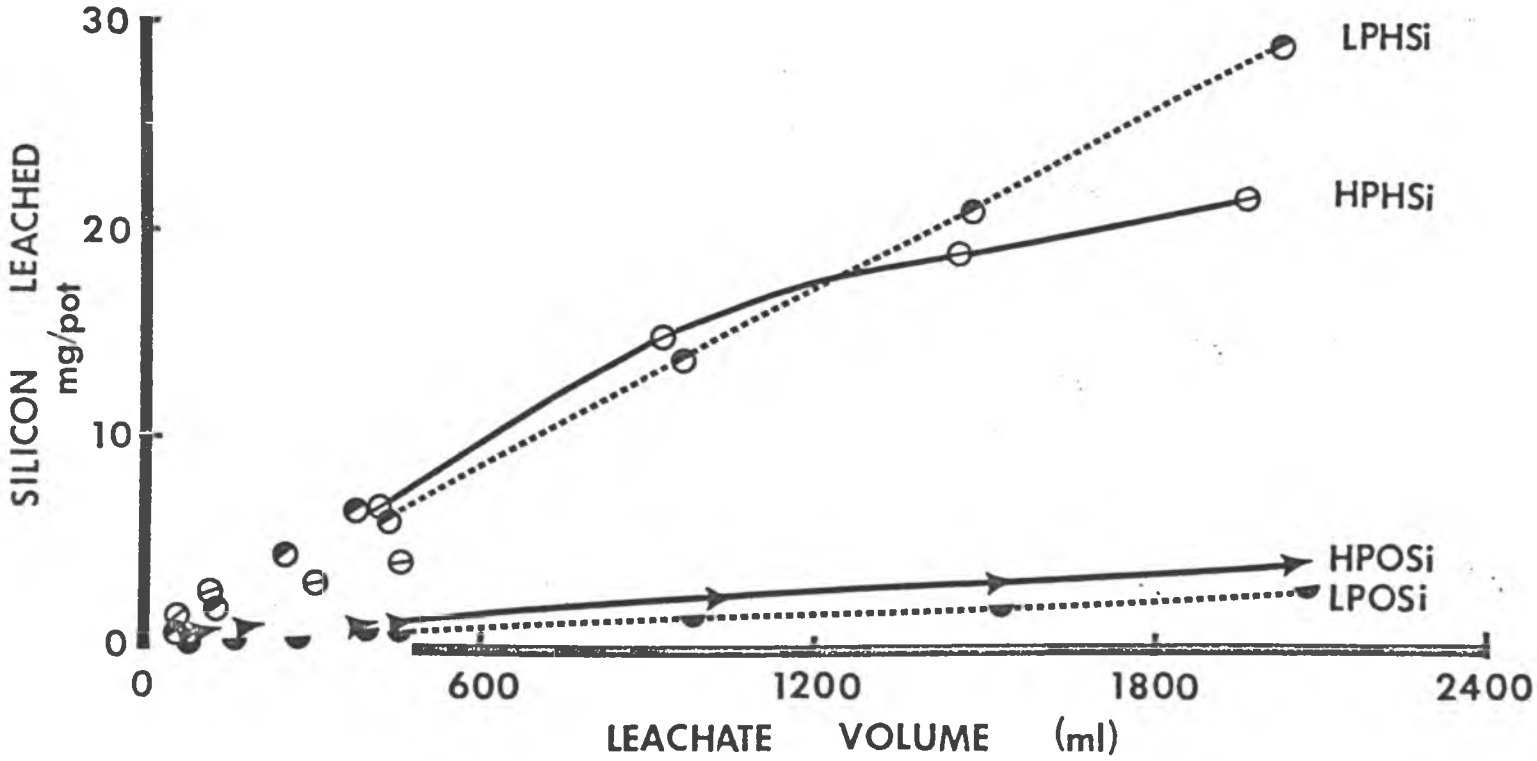

FIGURE 13. CUMMULATIVE Si LEACHED IN HALII SOIL AS A FUNCTION OF LEACHATE VOLUME. DATA POINTS JOINED BY DASHED OR SOLID LINE REPRESENT LEACHATE FROM HIGH WATER APPLICATION RATE; UNLINED REGION REPRESENTS LOW WATER APPLICATION RATE (LP = 100 ppm P, HP = 750 ppm P, OSi = ZERO Si AND HSi = 968 ppm Si)

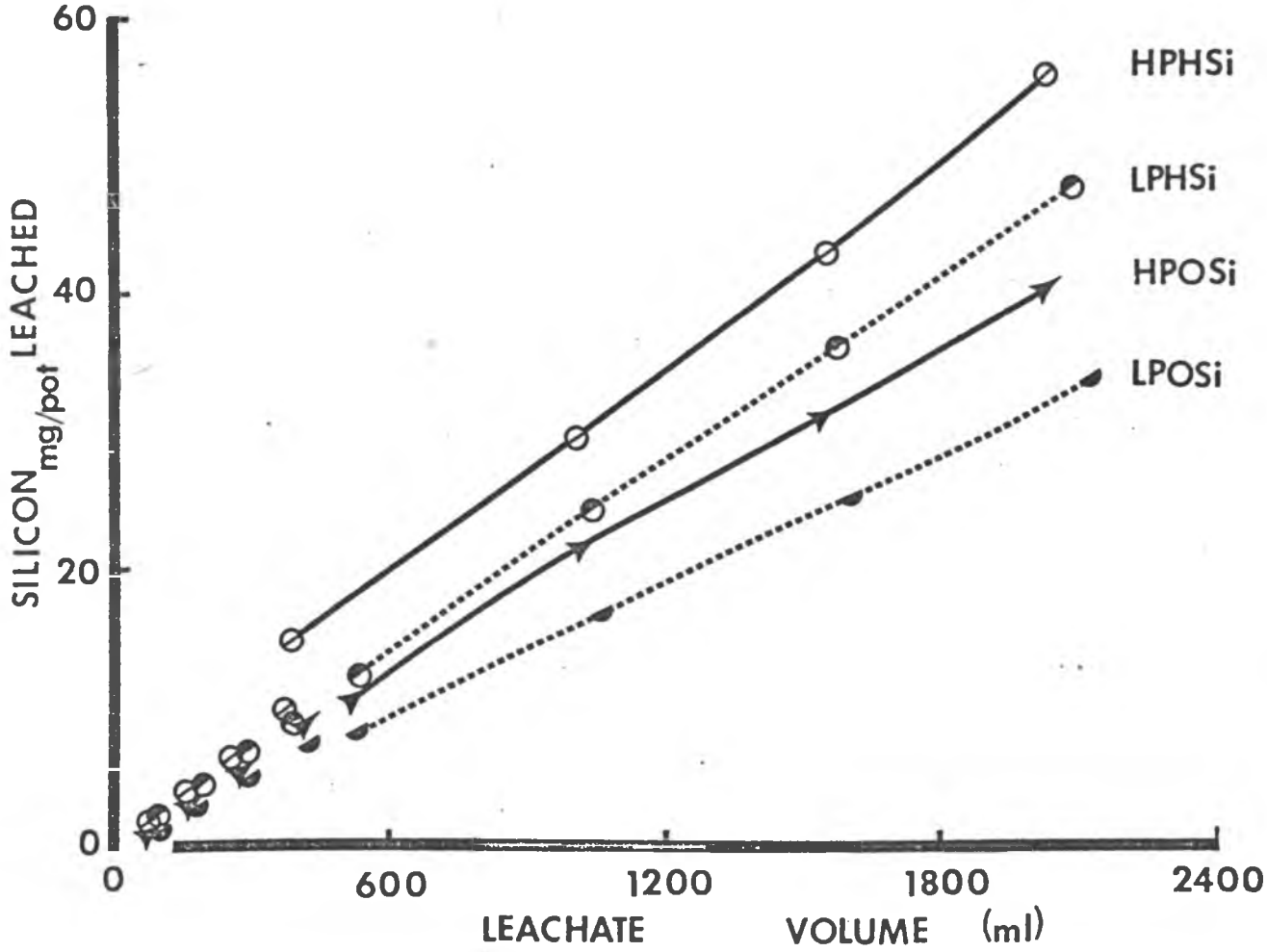

FIGURE 14. CUMMULATIVE Si LEACHED IN WAIMEA SOIL AS A FUNCTION OF LEACHATE VOLUME. DATA POINTS JOINED BY DASHED OR SOLID LINE REPRESENT LEACHATE FROM HIGH WATER APPLICATION RATE; UNLINED REGION REPRESENTS LOW WATER APPLICATION RATE (LP = 100 ppm P, HP = 750 ppm P, OSi = ZERO Si AND HSi = 968 ppm Si)

applied in several small increments than in one which received an equivalent amount of water in a single application. The data, at least for these soils, suggest that the opposite is true.

Two more points need to be clarified. The greater Na loss in the high Si treatments of the Halii soil can be attributed to Na contamination in $CaSiO_3$. In spite of this, this trend was not noted in the Waimea soil probably because the quantity of Na added as impurity was small relative to the quantity already present.

Lastly, the greater loss of Si from the low P, high Si (LPHSi) relative to the high P, high Si (HPHSi) treatments in the Halii soil can be attributed to greater Si plant adsorption in the high P treatment. This is expected to occur in the Halii but not in the Waimea as the Halii contains trace amounts of extractable Si, whereas applied Si in the Waimea was relatively small compared to the native extractable Si.

B. Plant Uptake

Phosphorus, silicon and irrigation treatments resulted in large differences in top growth of sorghum (Figure 15). In general, the healthier and larger sized plants had higher concentration of nutrients than smaller plants so that the proportion of the total extractable Ca, Mg, K, Na, P and Si stored in the plants differed greatly among treatments.

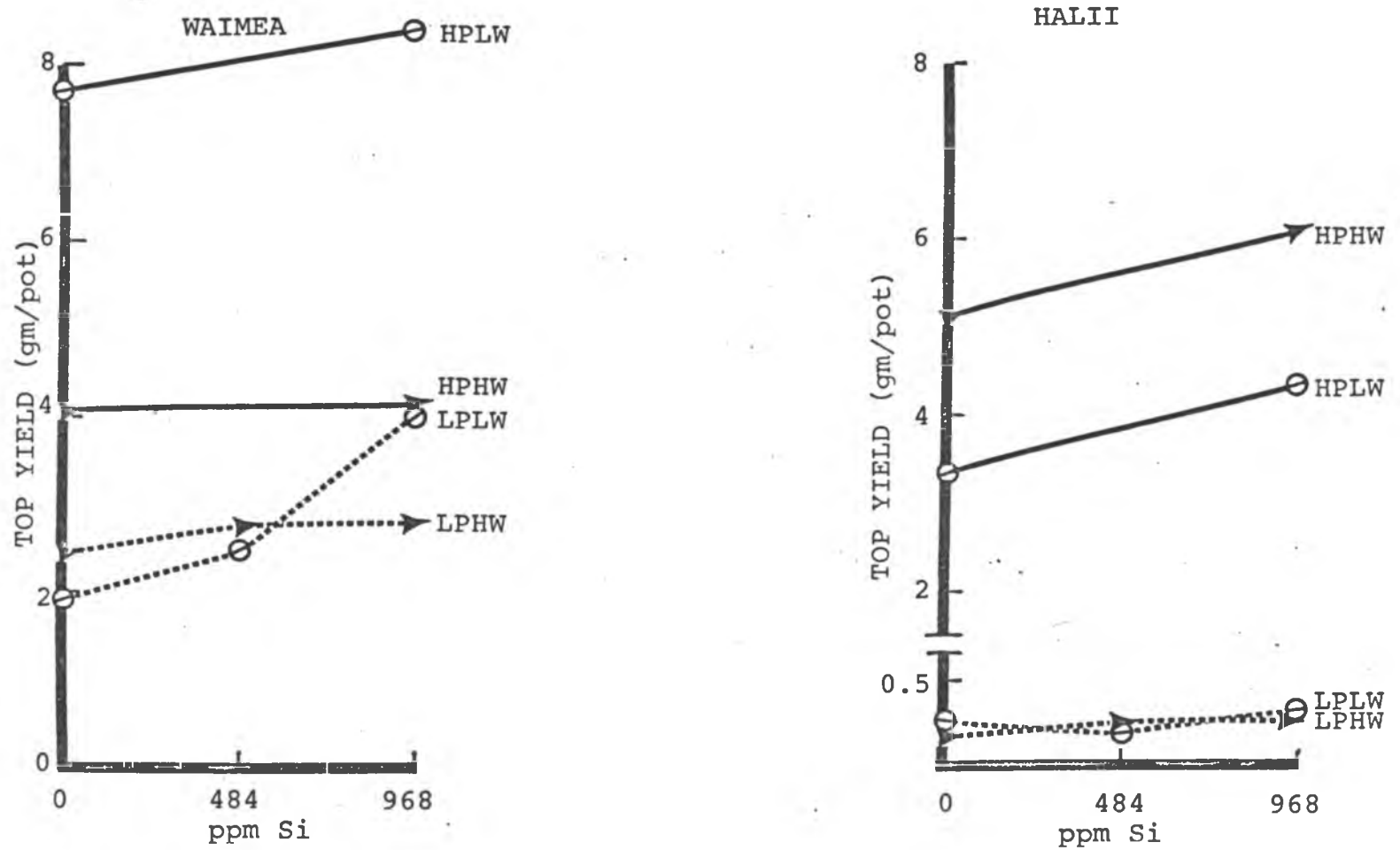

FIGURE 15. PLANT TOP YIELD (OVEN DRIED) IN THE HALII AND WAIMEA SOILS. (LP = 100 ppm P APPLIED, HP = 750 ppm P APPLIED, LW = LOW IRRIGATION RATE AND HW = HIGH IRRIGATION RATE

Plant yield was most strongly influenced by phosphorus application. The effect of Si on yield was small but significant. The high irrigation rate was better than the low rate in the Halii but the reverse was true in the Waimea soil. The last result is not unexpected but there remains the question of relating the result to either one of the two following factors. The Halii is a coarser (more aggregated) soil and therefore requires more water than the Waimea soil. Or, the Halii has a lower net negative charge and its colloids do not repel nitrate ions as effectively as colloids of the Waimea soil. Symptoms of nitrogen deficiency were apparent (chlorotic older leaves) in the high water application treatment in the Waimea soil.

Figures 16 to 19 summarize graphically tissue concentration and total uptake of nutrients by plants respectively. Since the quantity of nutrients extracted from the soil by plants varies greatly, and since in many cases, treatments that resulted in low leaching loss are the same treatments that resulted in heavy removal of nutrients by plants, there arises a need to establish whether low leaching is related to plant removal or greater ion retention by colloids. This answer lies in the soil data which follow.

C. Soil

The influence of Si, P and irrigation rate on ion retention by the soil is illustrated in Figures 20 to 21.

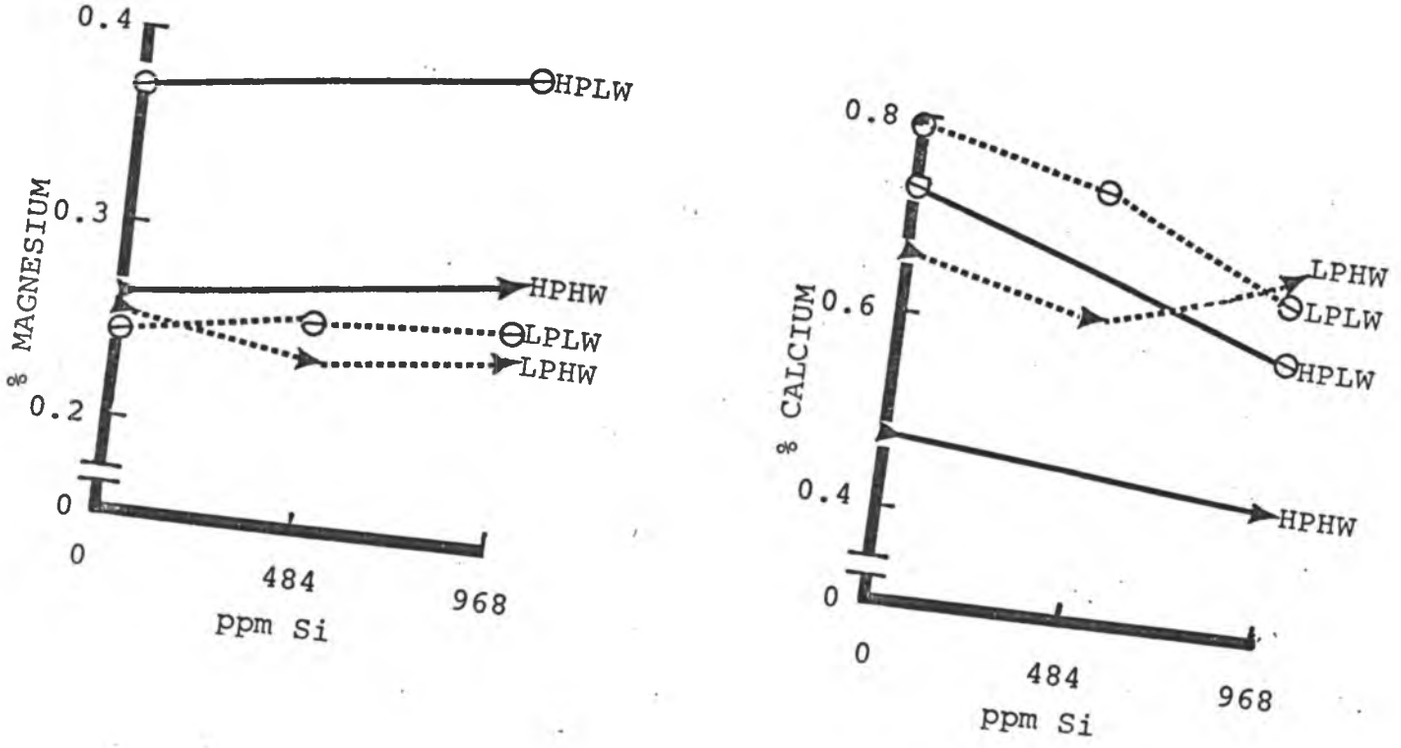

FIGURE 16a. CONCENTRATIONS OF Ca AND Mg IN PLANT TOPS OF THE HALII SOIL

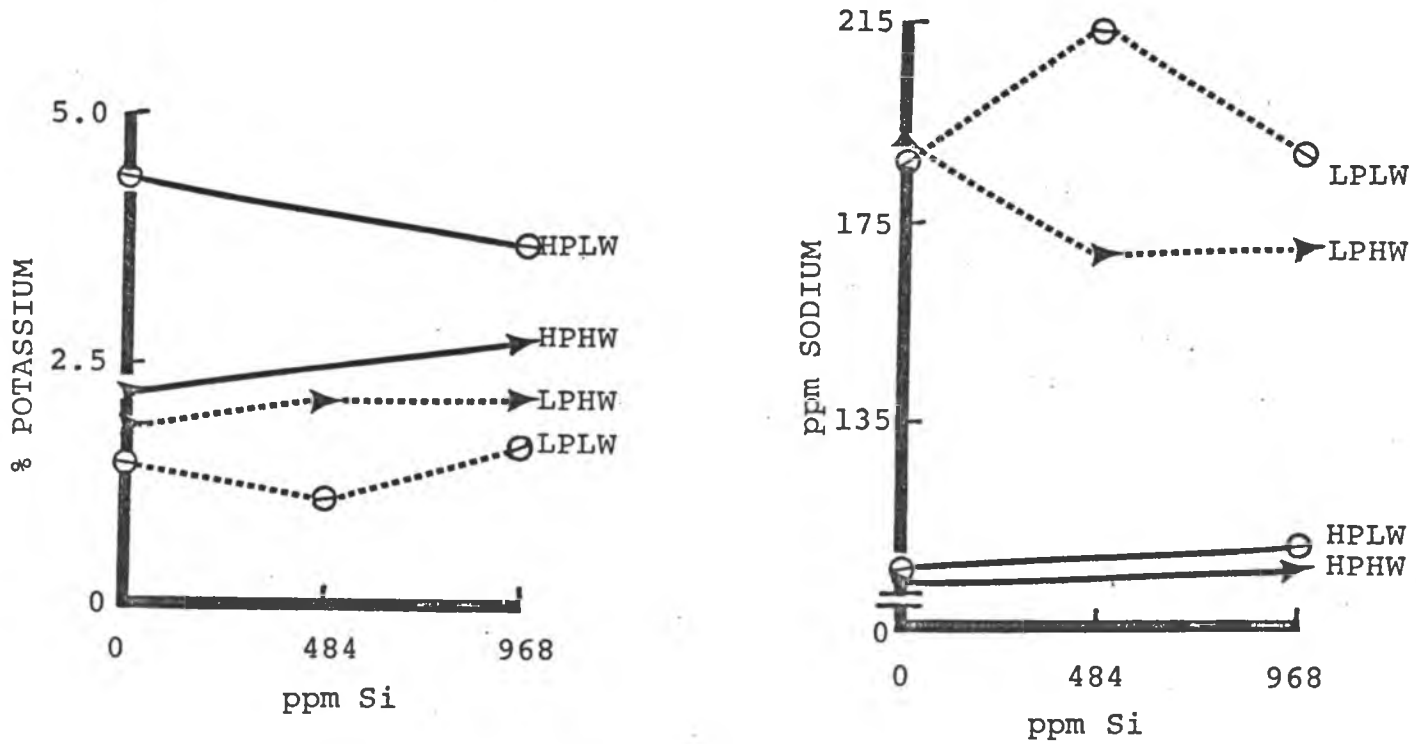

FIGURE 16b. CONCENTRATIONS OF K AND Na IN PLANT TOPS OF THE HALII SOIL

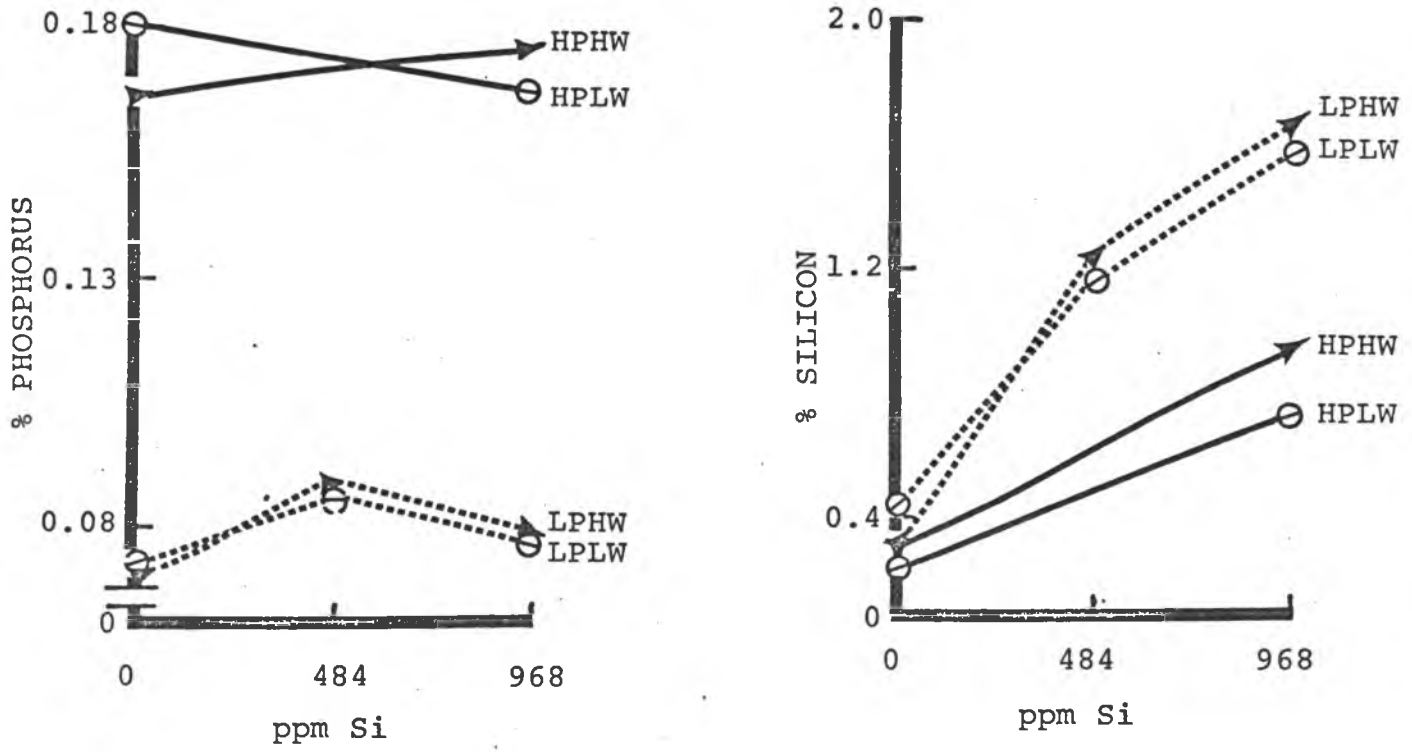

FIGURE 16c.. CONCENTRATIONS OF P AND Si IN PLANT TOPS OF THE HALII SOIL

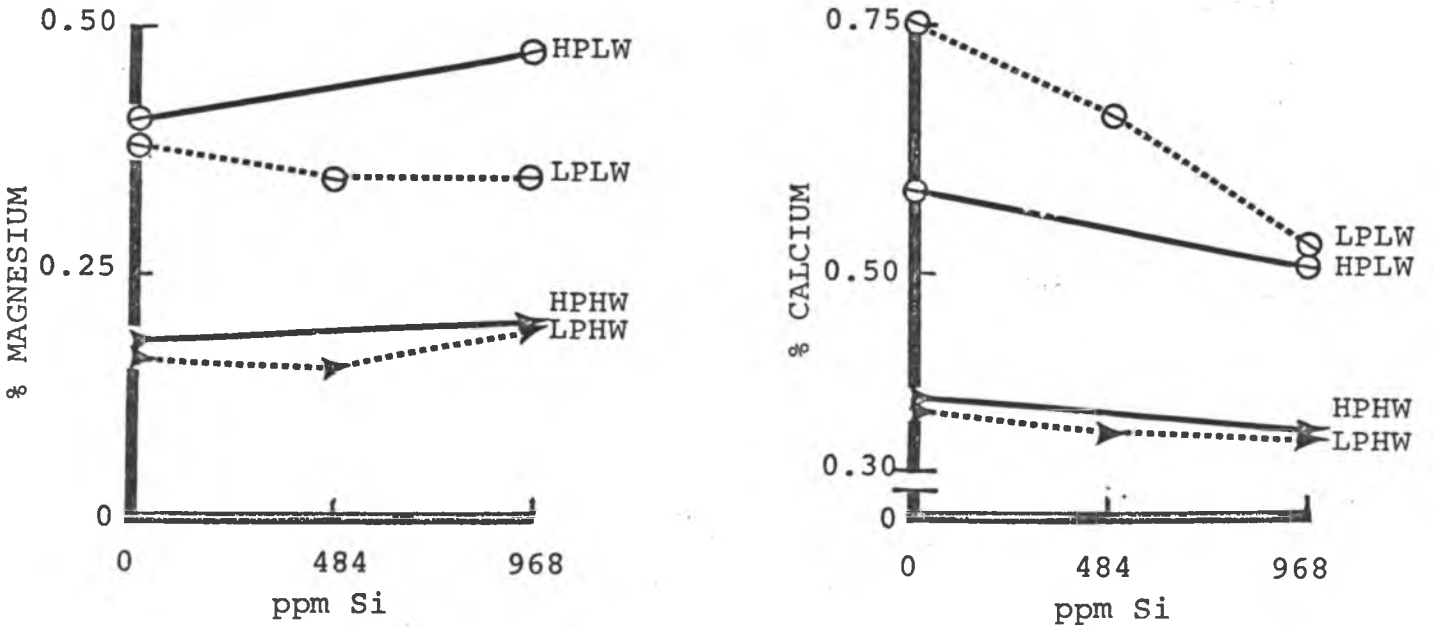

FIGURE 17a. CONCENTRATIONS OF Ca AND Mg IN PLANT TOPS OF THE WAIMEA SOIL

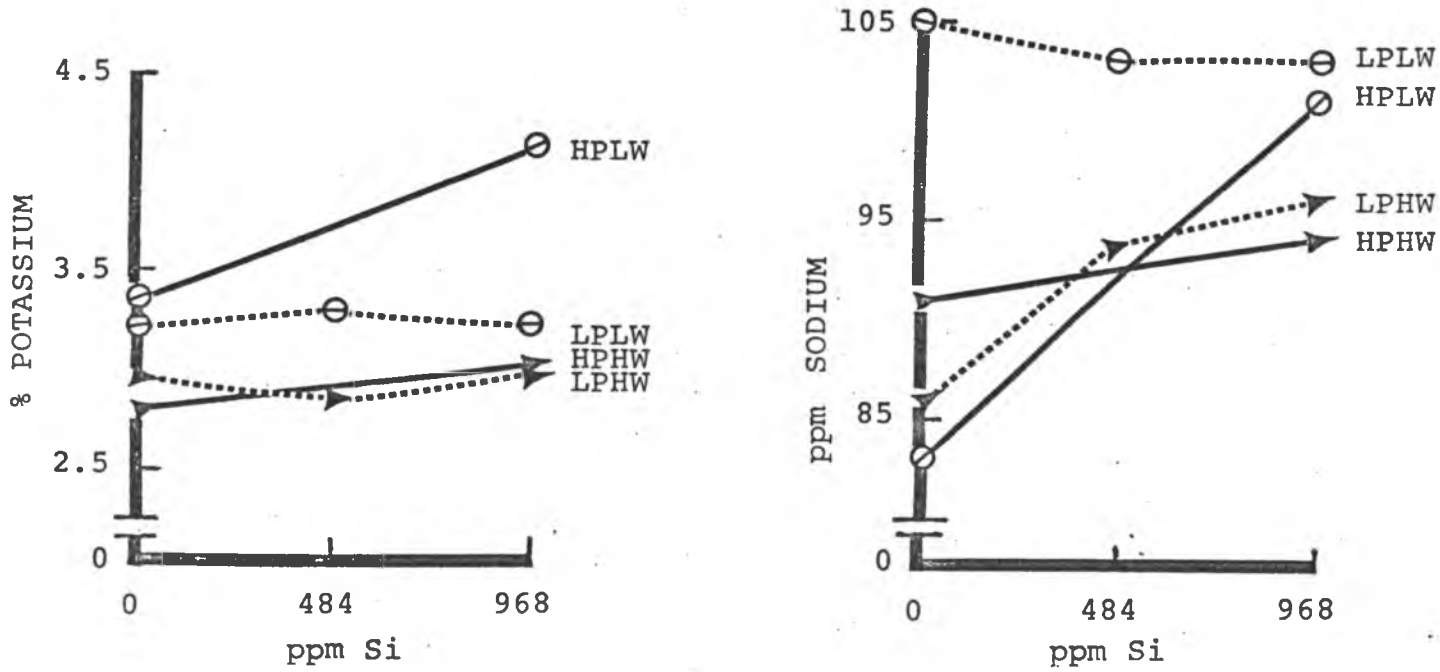

FIGURE 17b. CONCENTRATIONS OF K AND Na IN PLANT TOPS OF THE WAIMEA SOIL

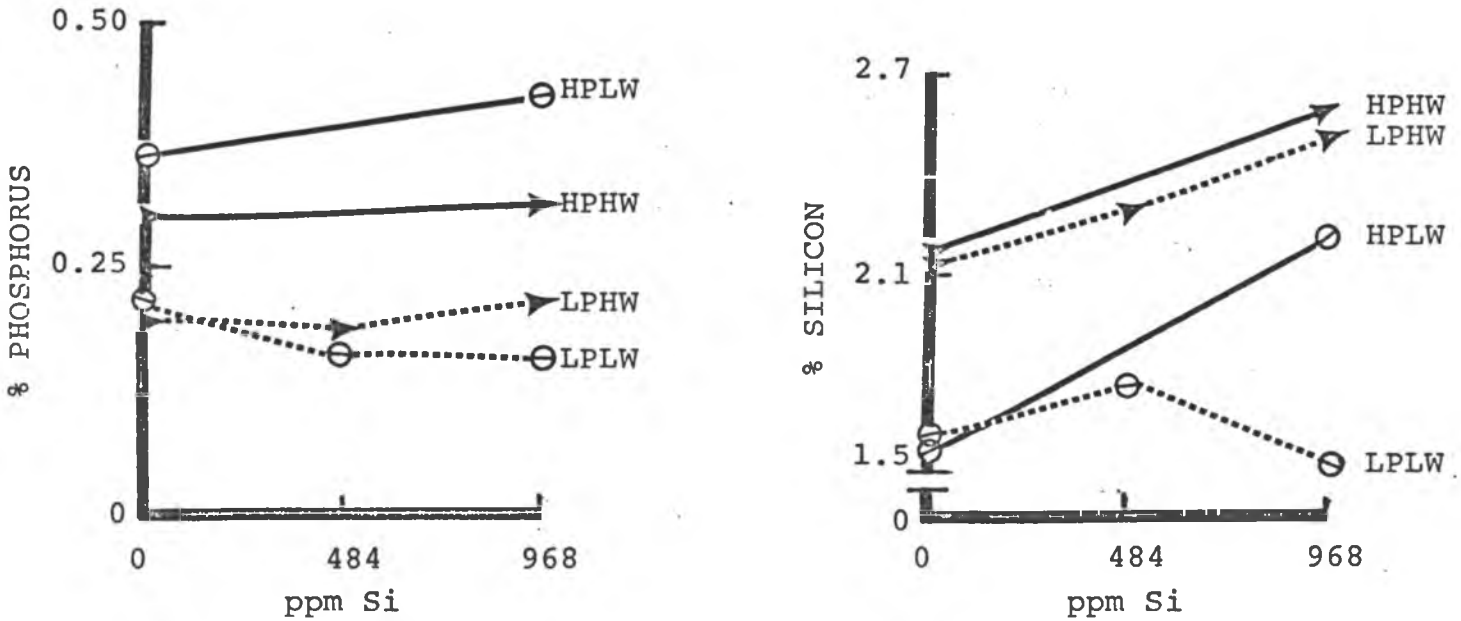

FIGURE 17c. CONCENTRATIONS OF P AND Si IN PLANT TOPS OF THE WAIMEA SOIL

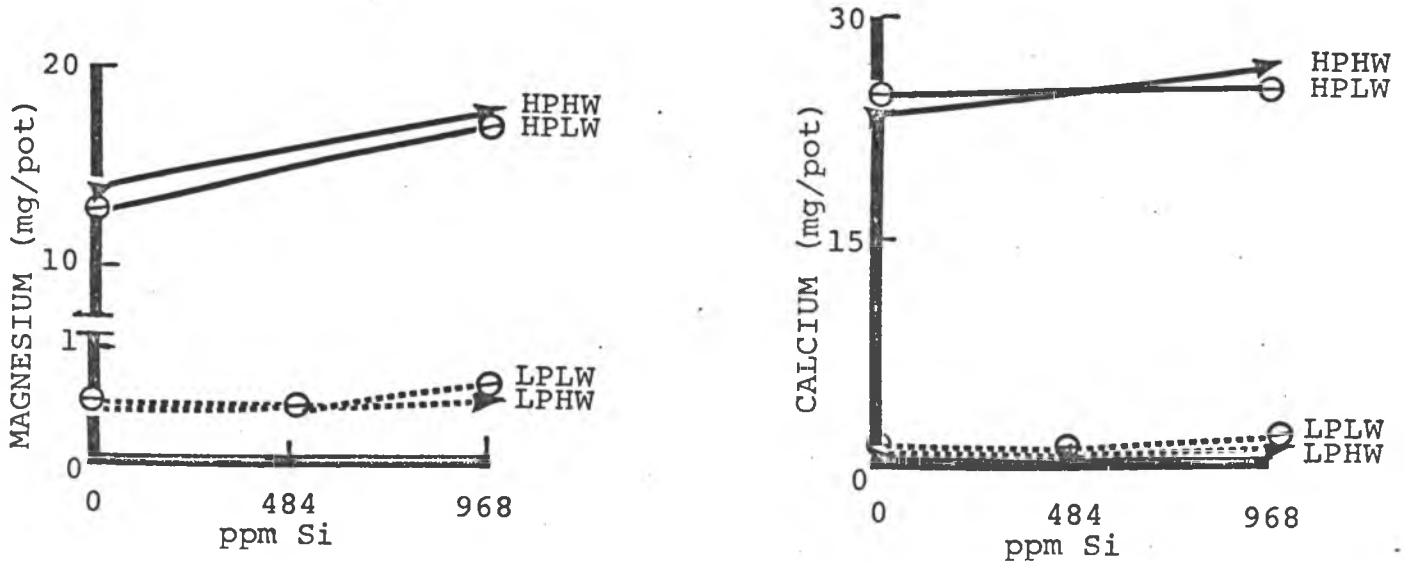

FIGURE 18a. TOTAL UPTAKE OF Ca AND Mg IN PLANT TOPS OF THE HALII SOIL

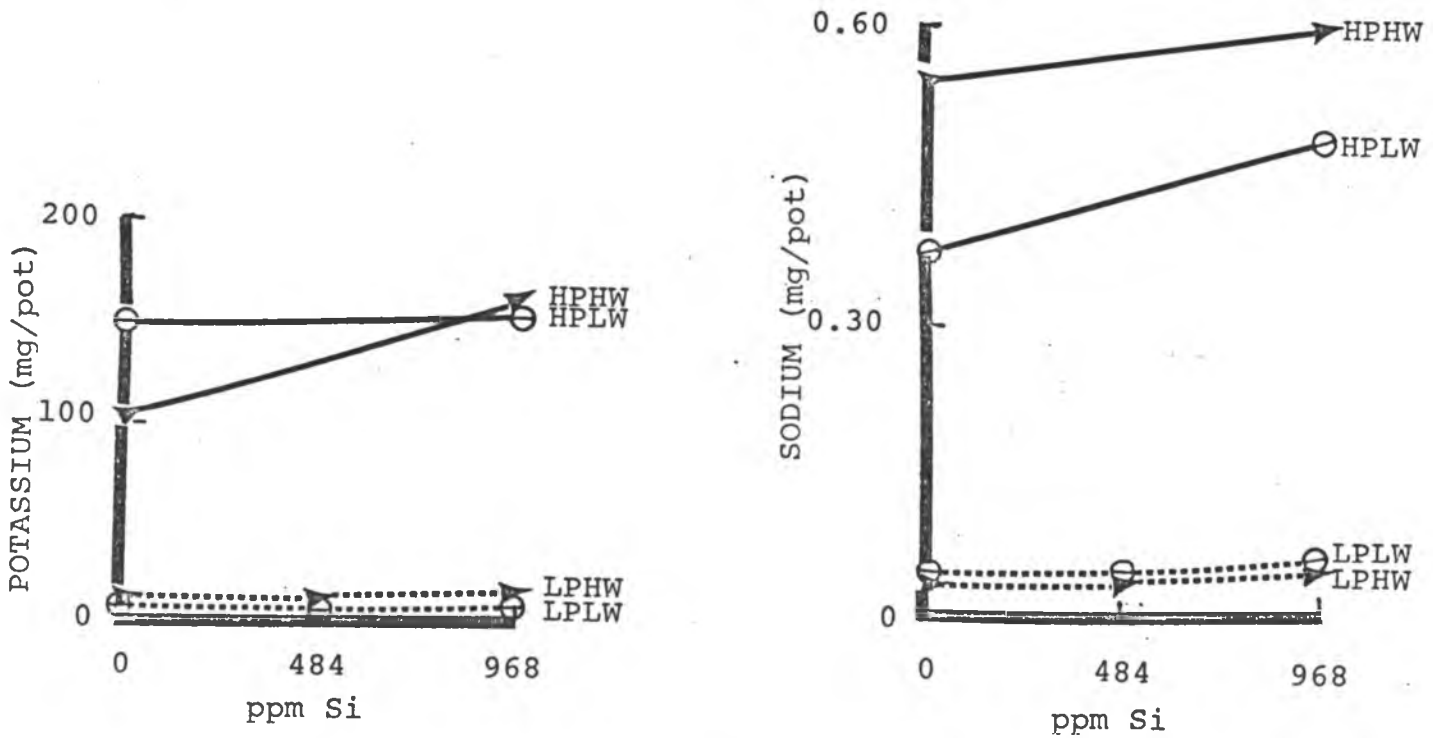

FIGURE 18b. TOTAL UPTAKE OF K AND Na IN PLANT TOPS OF THE HALII SOIL

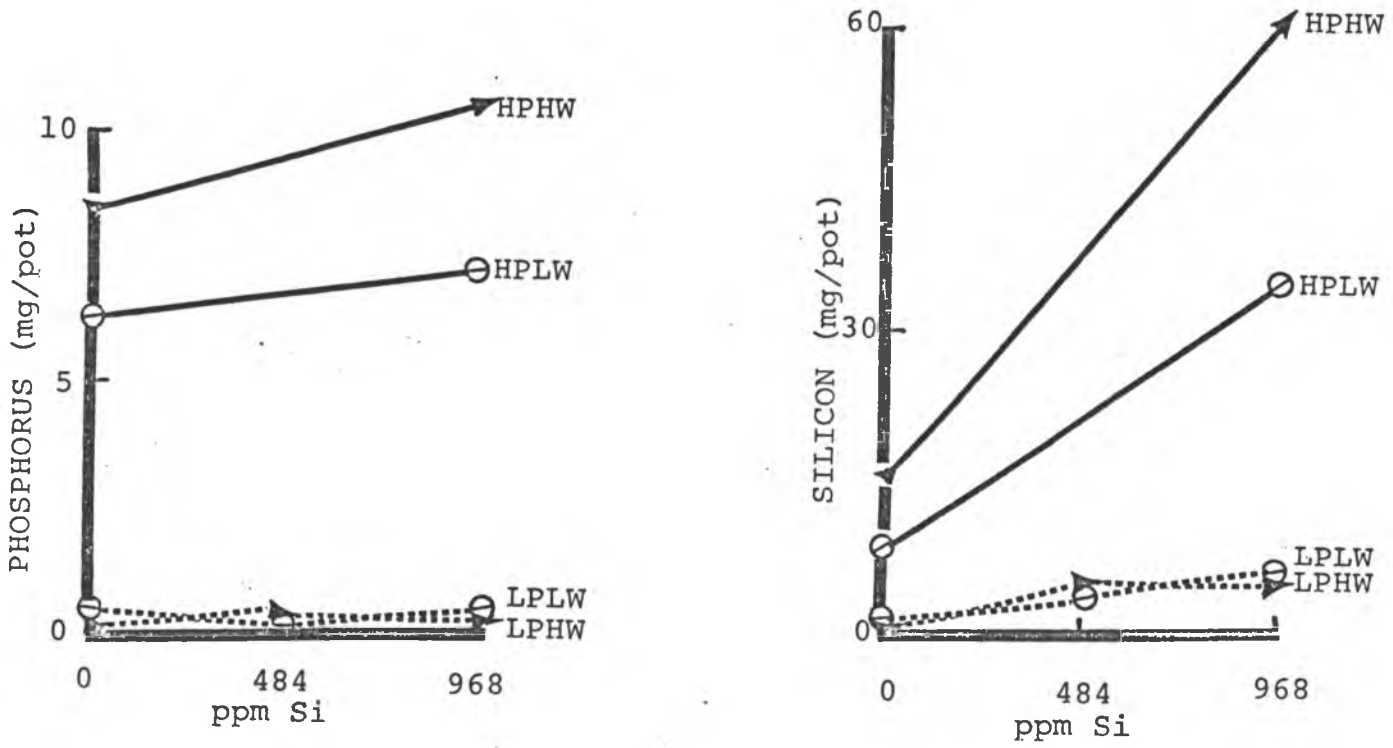

FIGURE 18c. TOTAL UPTAKE OF P AND Si IN PLANT TOPS OF THE HALII SOIL

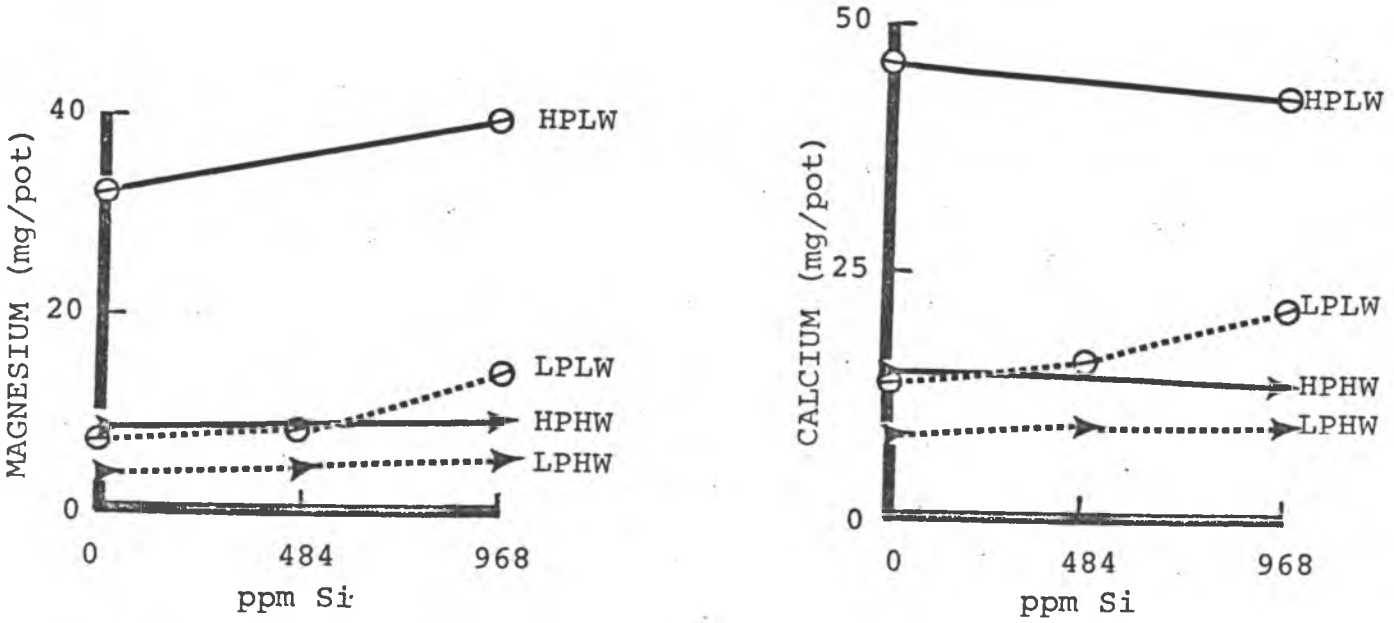

FIGURE 19a. TOTAL UPTAKE OF Ca AND Mg IN PLANT TOPS OF THE WAIMEA SOIL

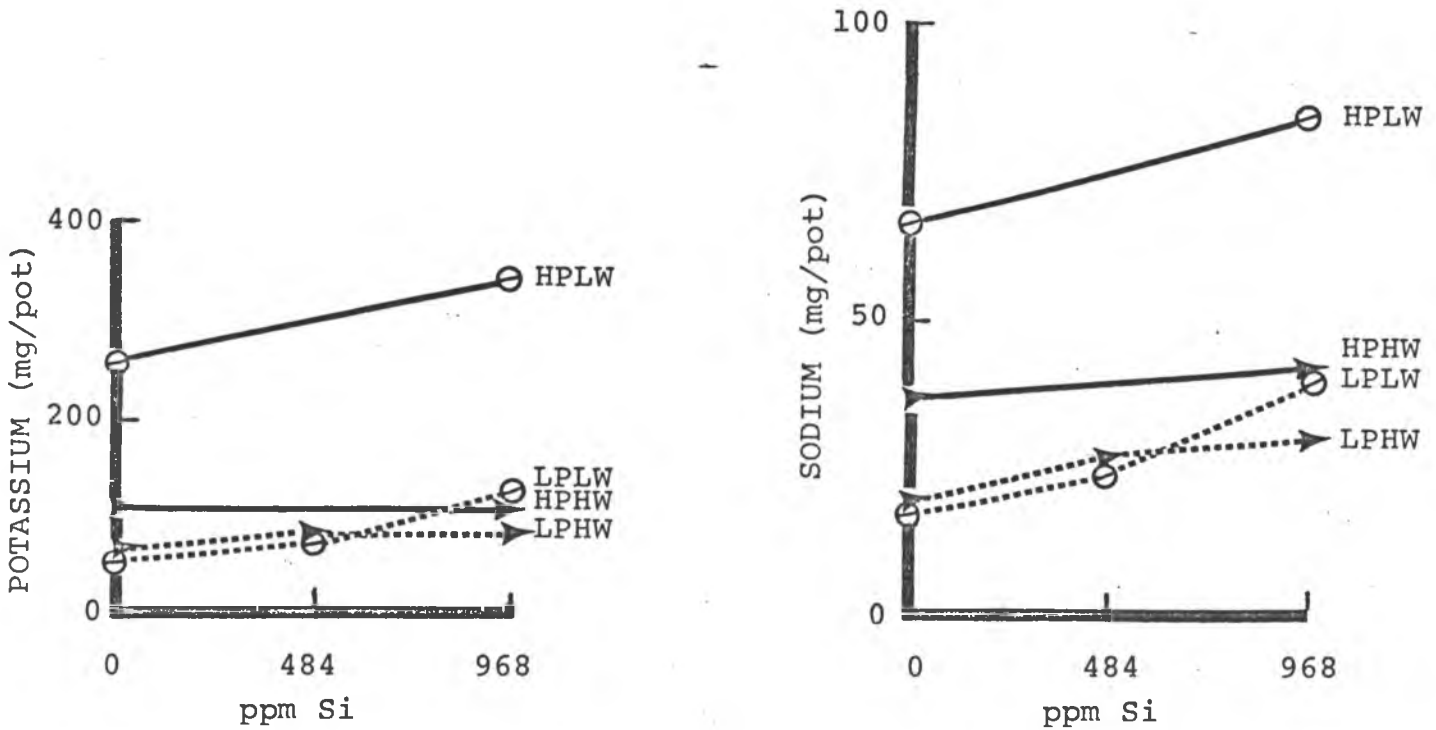

FIGURE 19b. TOTAL UPTAKE OF K AND Na IN PLANT TOPS OF THE WAIMEA SOIL

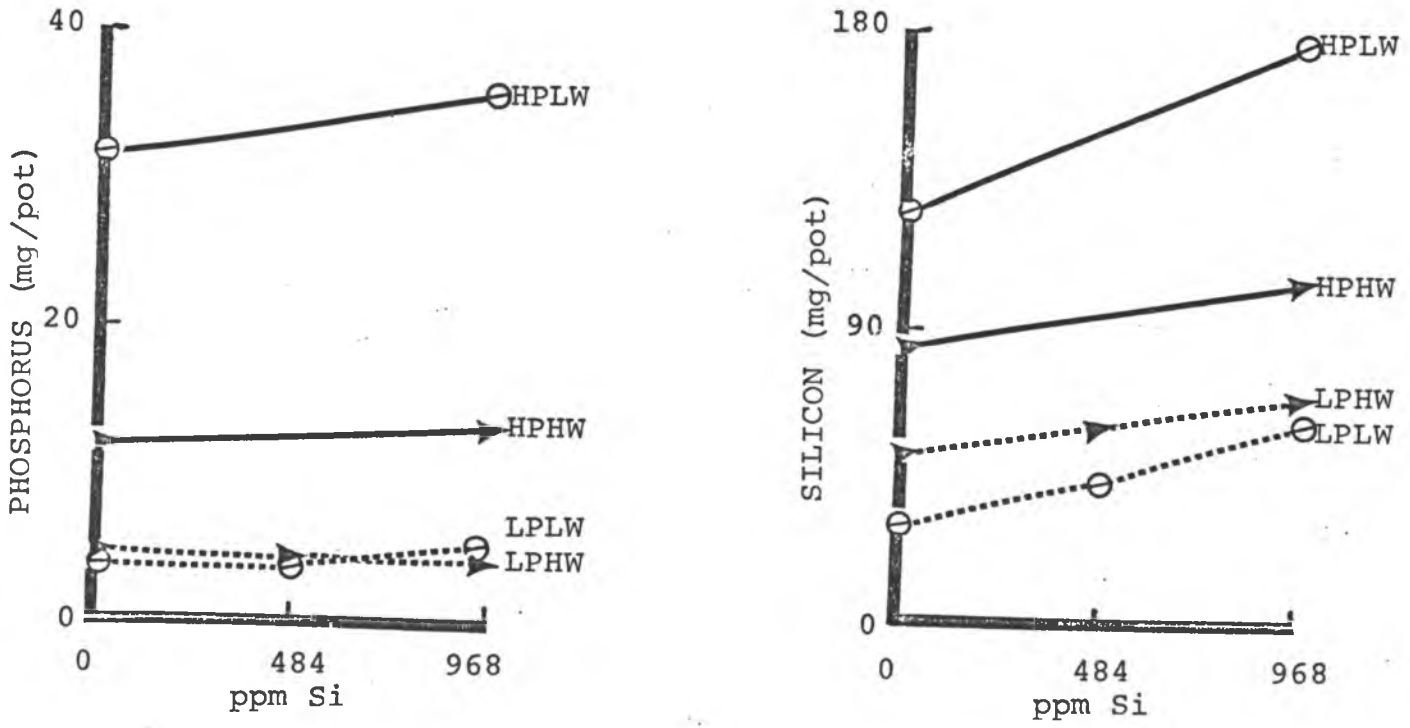

FIGURE 19c. TOTAL UPTAKE OF P AND Si IN PLANT TOPS OF THE WAIMEA SOIL

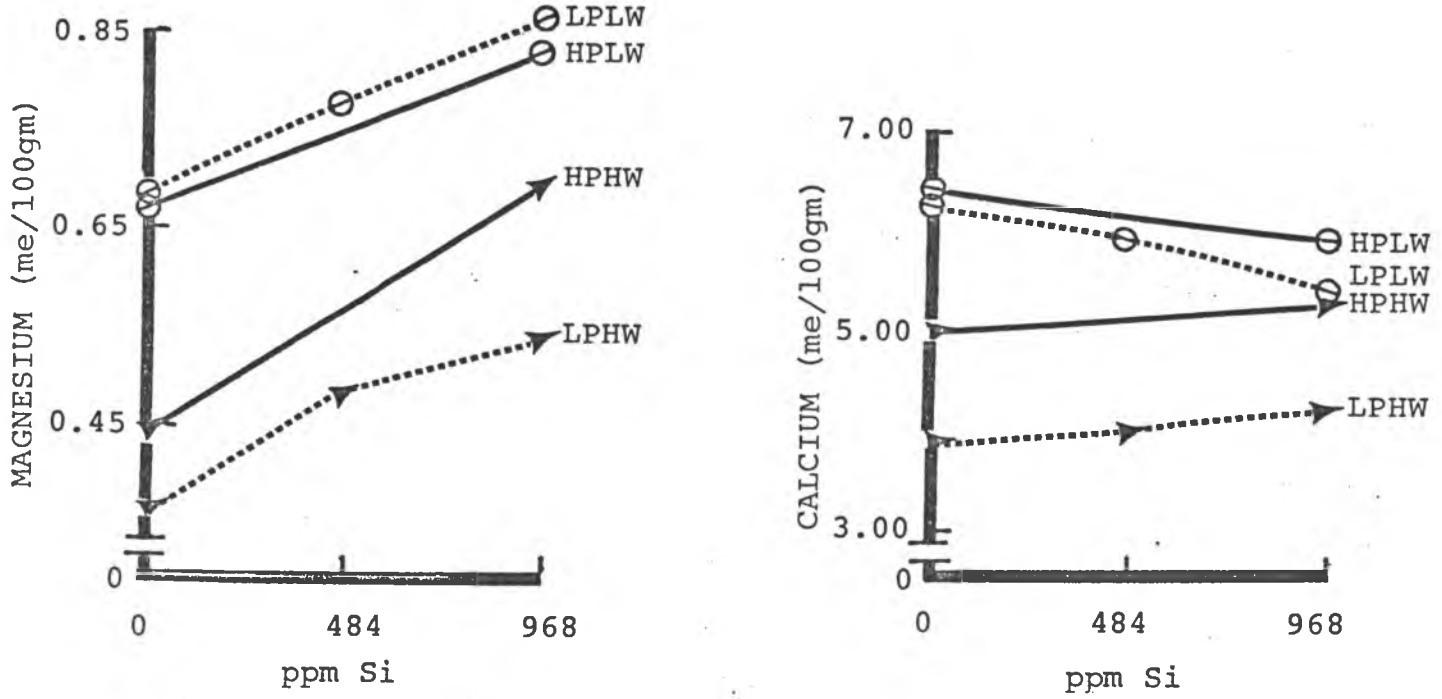

FIGURE 20a. EXCHANGEABLE Ca AND Mg IN THE HALII SOIL, AFTER LOW (LW) AND HIGH (HW) WATER TREATMENTS

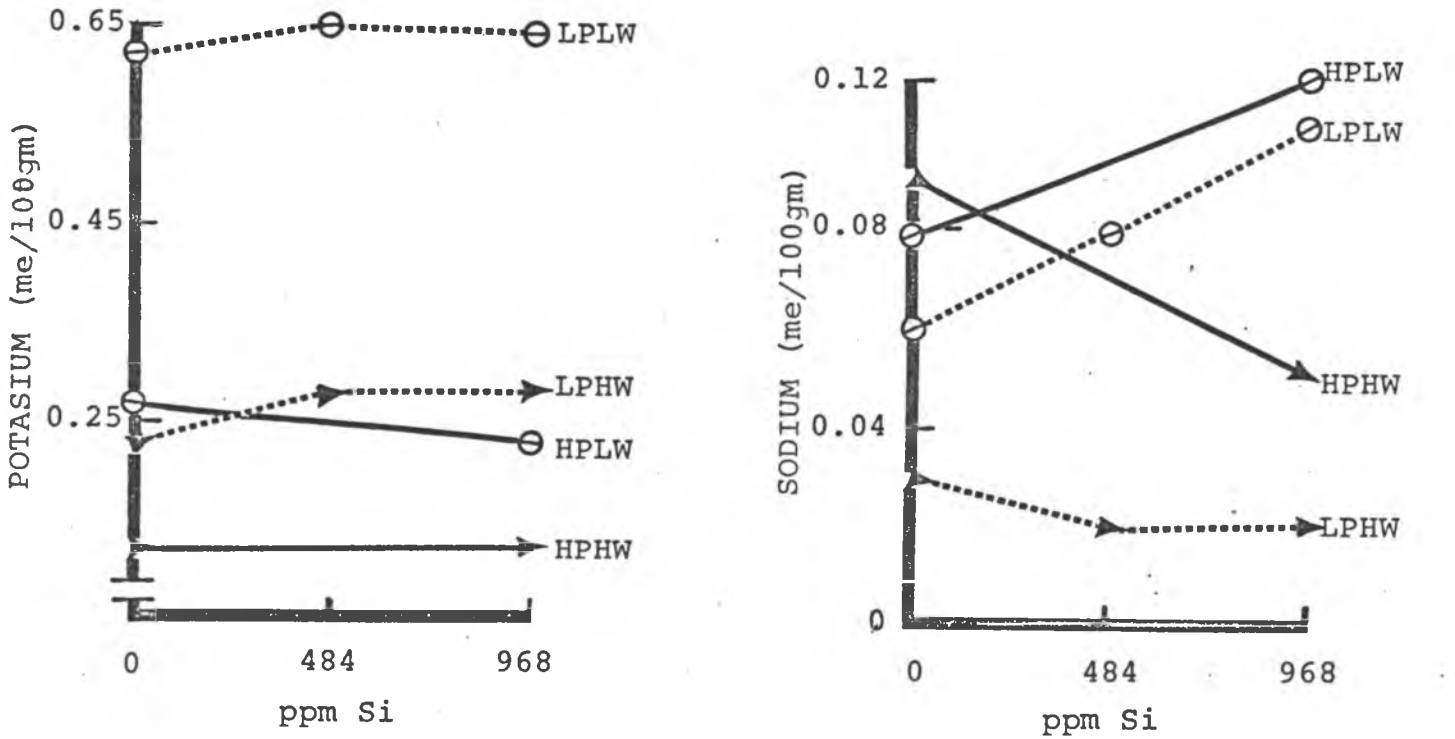

FIGURE 20b. EXCHANGEABLE K AND Na IN THE HALII SOIL, AFTER LOW (LW) AND HIGH (HW) WATER TREATMENTS

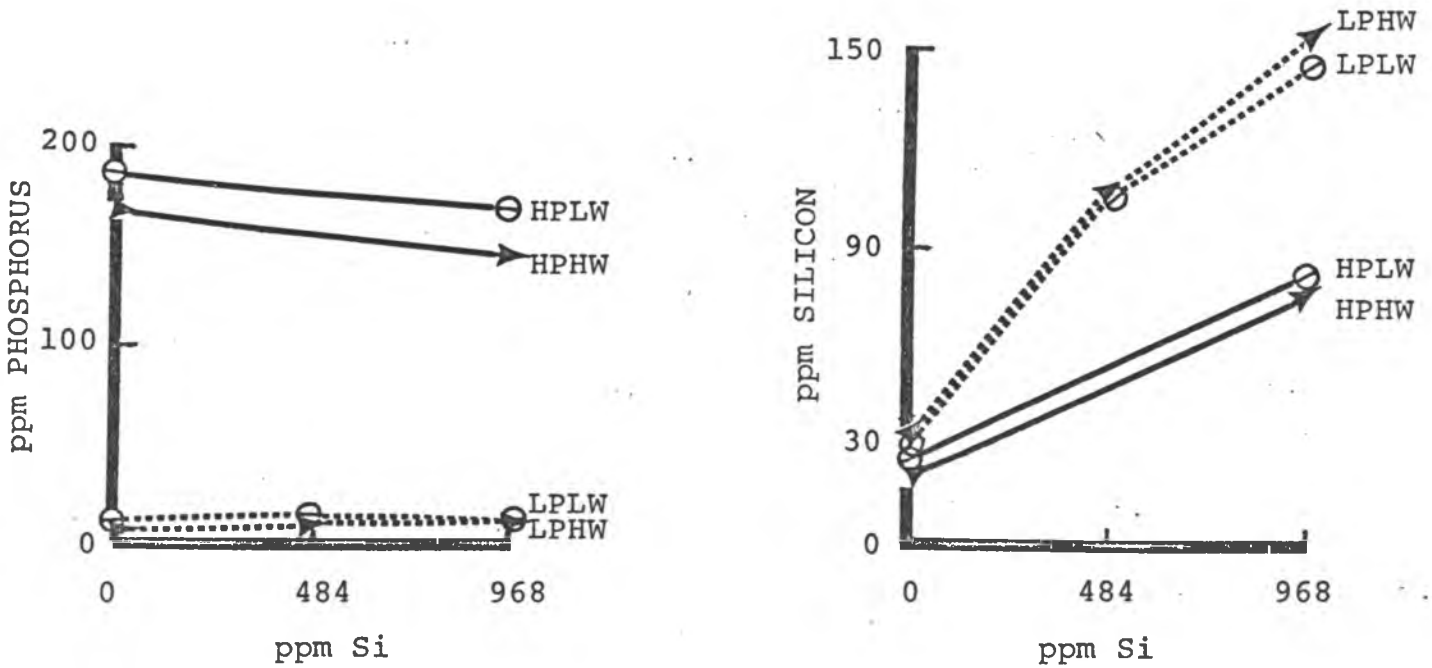

FIGURE 20c. EXTRACTABLE P AND Si IN THE HALII SOIL, AFTER LOW (LW) AND HIGH (HW) WATER TREATMENTS

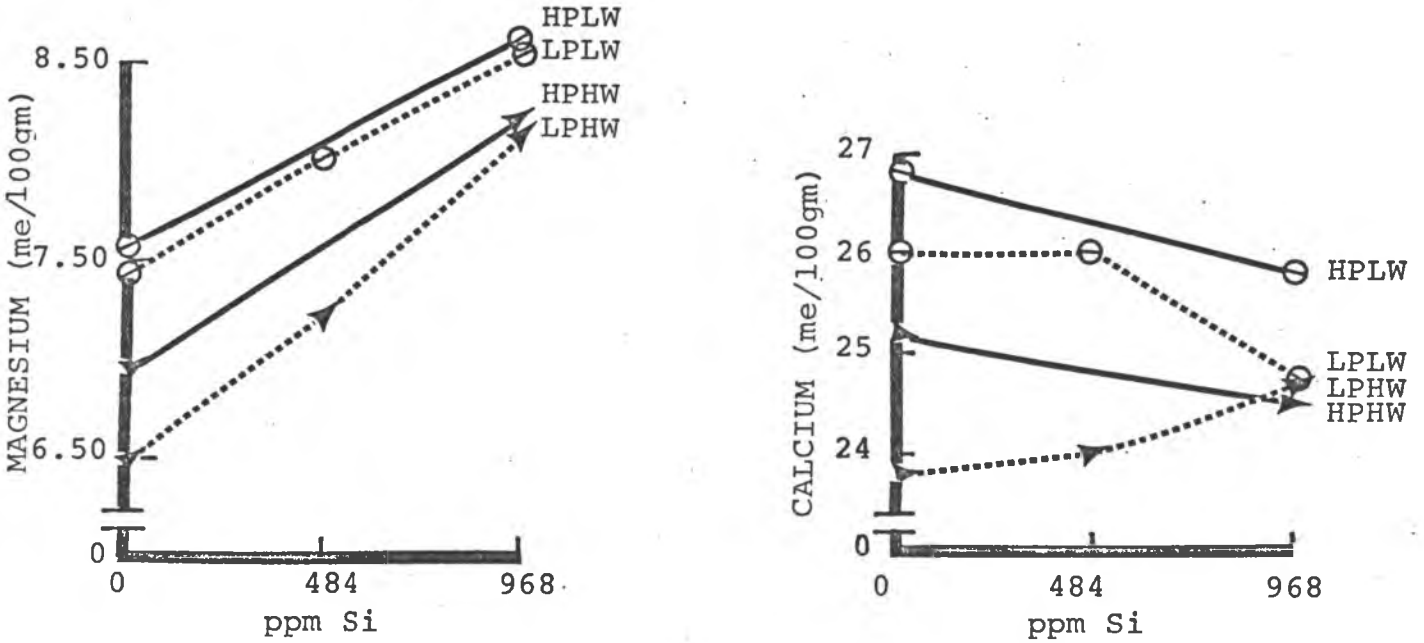

FIGURE 21a. EXCHANGEABLE Ca AND Mg IN THE WAIMEA SOIL, AFTER LOW (LW) AND HIGH (HW) WATER TREATMENTS

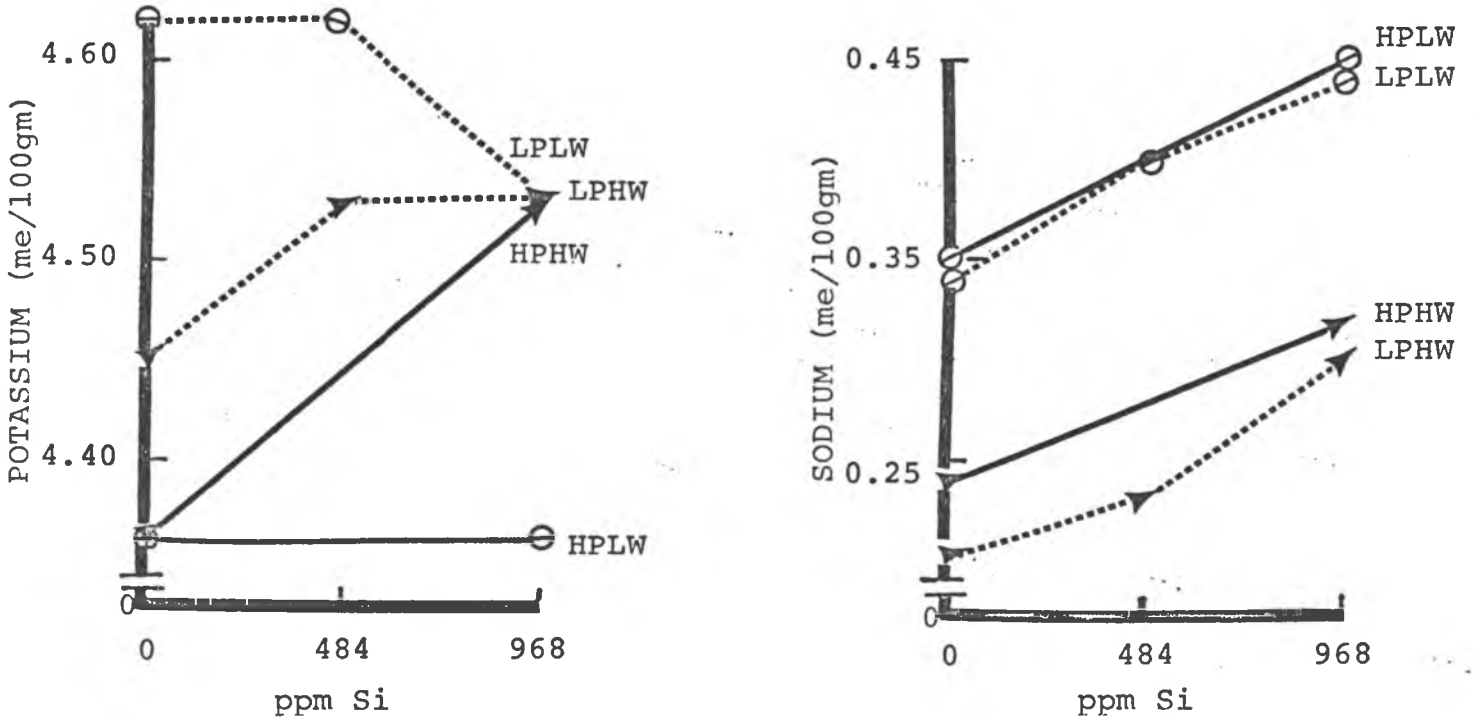

FIGURE 21b. EXCHANGEABLE K AND Na IN THE WAIMEA SOIL, AFTER LOW (LW) AND HIGH (HW) WATER TREATMENTS

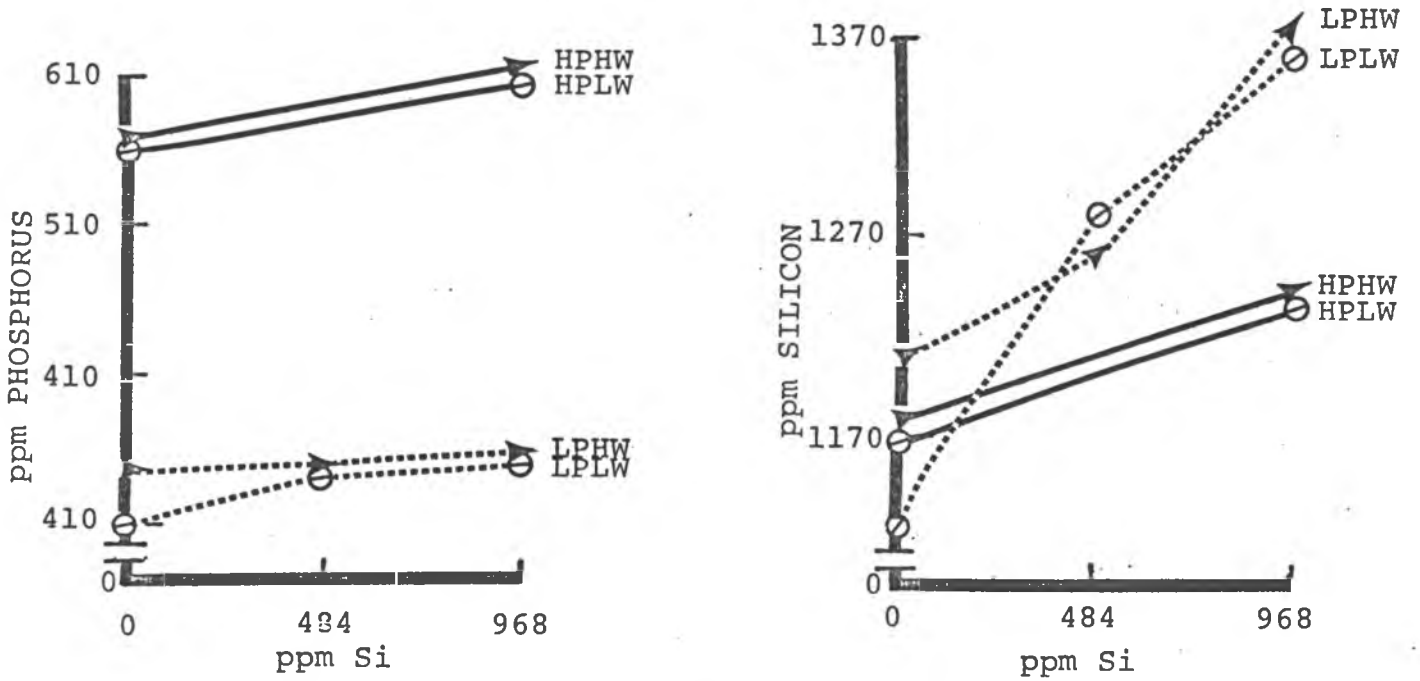

FIGURE 21c. EXTRACTABLE P AND Si IN THE WAIMEA SOIL, AFTER LOW (LW) AND HIGH (HW) WATER TREATMENTS

While cation retention tends to increase with increasing Si and P application, several exceptions appear.

Sodium retention decreases with increasing Si application for the heavy irrigation rate in the Halii soil probably because there is more Na to leach in the high Si treatment. The reader should recall that Na was an impurity of $CaSiO_3$. There is a strong interaction between Si and water application on Na retention.

Another exception to the effect of Si or P on soil cation retention is with K. In the low irrigation rate of the Waimea, K retention is independent of or decreases with increasing Si application. This trend is related to the greater plant uptake of K in the low irrigation treatment. Note that the high P, low irrigation rate (HPLW) of the Waimea occupies the same relative position on the K graph as the high P, high irrigation rate (HPHW) of the Halii soil. The low level of soil K in this treatment corresponds to a large plant uptake of the element.

The most interesting exception to the general trend is found in the Ca data. In several treatments (see Figures 20 and 21), exchangeable Ca decreases with increasing Si application. This occurred inspite of the fact that Ca lost in the leachate decreased with increasing Si application, and the fraction of the total amount removed by the plant was negligible. It will be shown in the next section that about one half of the Ca added to the Halii soil could not be accounted for in the leachate,

plant or exchangeable form.

Unlike Mg, K and Na, P and Si are specifically adsorbed on surfaces of colloids. Most extractants succeed in removing only a small part of the adsorbed anion. In general, one would find that the quantity of adsorbate extracted increases as the adsorbate concentration increases. While more adsorbate is removed per unit mass of adsorbant at high adsorbate concentration, a smaller fraction of the total adsorbate concentration is extracted.

The extractable soil Si increases with increasing Si application in both soils. At the high Si rates, application of high P suppresses Si extraction. This is probably related to the fact that in the high P, high Si treatment (HPHSi), the capacity of the extract to remove anions is limited.

Extractable soil P increased with increasing P application. Extractable P increased with increasing Si application in the Waimea soil but decreased with increasing Si in the Halii soil. Greater plant uptake of P in the high P, high Si treatment (HPHSi) in the Halii relative to the high P, zero Si treatment (HPOSi) probably accounts for the reduced extractable P in the high Si treatments.

Effect of P and Si application on CEC. The design of the experiment was based on the assumption that application of P and Si would increase CEC and therefore increase cation retention. It turns out that application of P reduces CEC. The reduction in CEC due to P is statistically

significant.

There is also a suggestion that when the applied phosphorus level is low, CEC decreased with increasing Si application.

It is not possible to give an adequate explanation for this observation until a full account of the cation distribution in the leachate, plant and soil is made. It will be shown in the next section that while net charge does not in fact increase with increasing P or Si application, the charge is neutralized by specifically adsorbed calcium ions.

Soil pH. Although the initial soil pH for all treatments were adjusted to a constant value for a given soil, the final pH differed with treatment (Figures 22 and 23). This is not surprising since the amounts of ions leached or extracted by the plants differed considerably among treatments.

Soil pH generally tends to increase with increasing Si application probably because more Ca is specifically adsorbed. This point will be explained in more detail in a later section.

In the Halii soil, the highest pH's were measured in the soils which had received the largest volume of irrigation water. In short, leaching raised soil pH. This is related to the higher electrolyte concentration in the low irrigation treatments. In negatively charged colloid, increasing the electrolyte concentration reduces the pH as

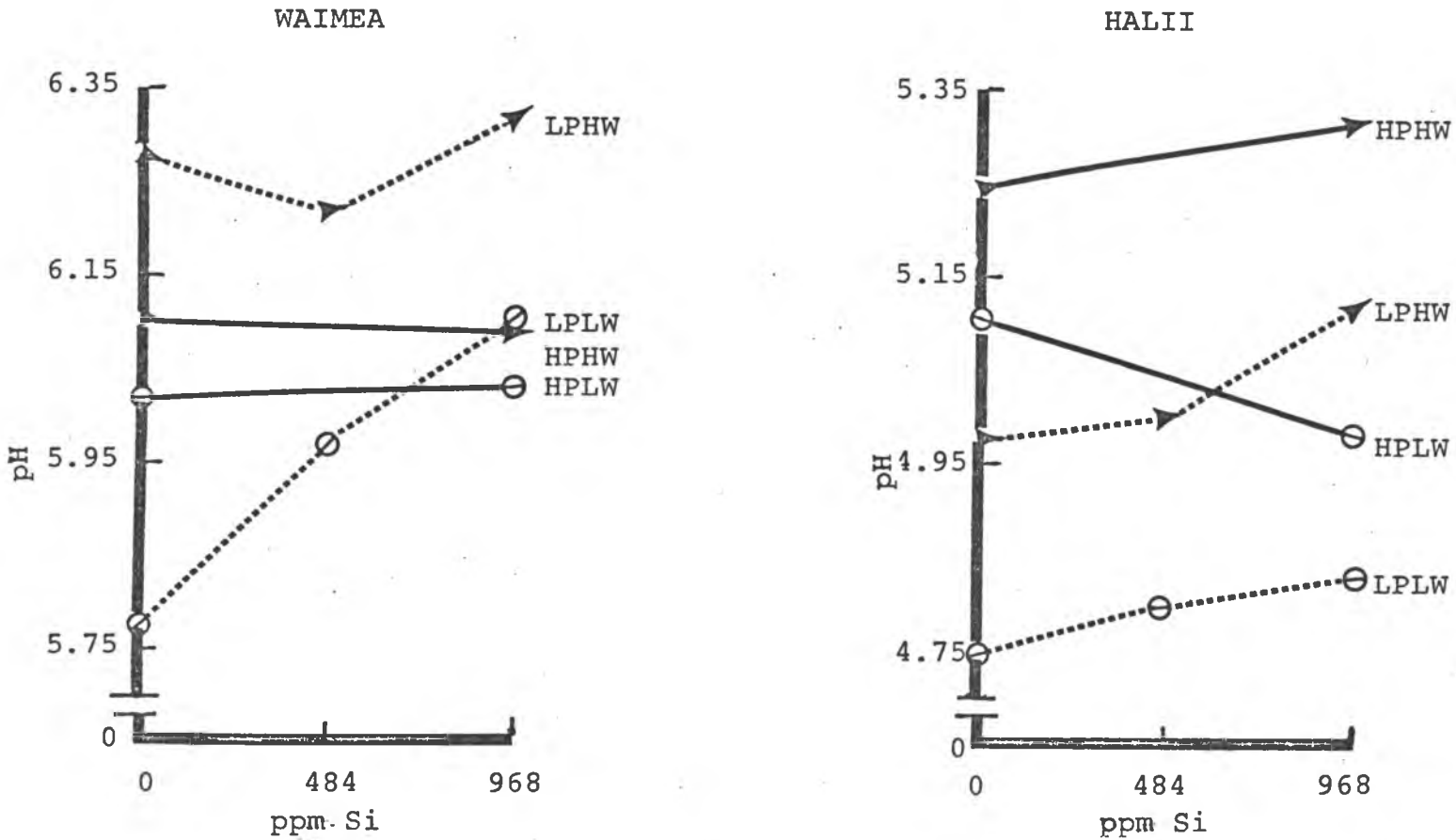

FIGURE 22. pH IN WATER PASTES OF THE HALII AND WAIMEA SOILS, AFTER LOW (LW) AND HIGH (HW) WATER TREATMENTS

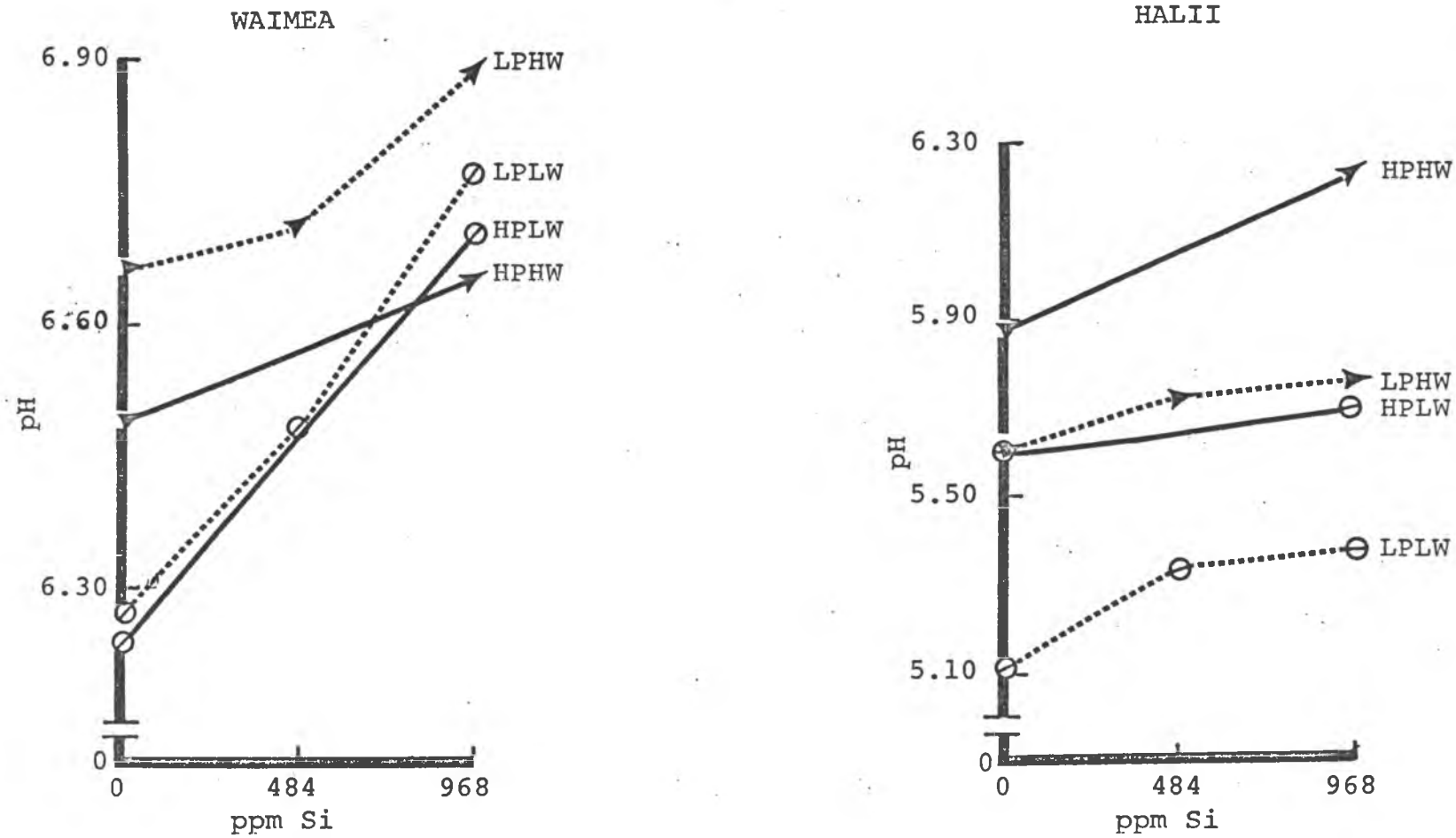

FIGURE 23. pH IN 1:5 WATER DILUTIONS OF THE HALII AND WAIMEA SOILS, AFTER LOW (LW) AND HIGH (HW) WATER TREATMENTS

predicted by Δ pH values (Mekaru and Uehara, 1972).

This explanation fails when applied to the high P, high irrigation treatment of the Waimea soil. Experimental error or some unknown mechanism may account for it.

D. Distribution of Cations and Anions in Leachate, Plant and Soil

Each cation (Ca, Mg, K, Na) or anion (P, Si) in the leachate, plant and soil was expressed as a percentage of the total quantity measured at the beginning of the experiment. These data are presented graphically in Figures 24 to 35. The quantity present as native forms (exchangeable Ca, Mg, K, Na or extractable P, Si) plus the amount added as fertilizer or ammendment was used as the total. For example, total K in the Halii soil was 310 ppm, consisting of 60 ppm native and 250 ppm applied.

For a given soil total Ca, Mg and K were held constant for all treatments. Unintentionally, Na became a variable because it was added as an impurity of $CaSiO_3$. Total P and Si were variables. While the amount of P or Si applied for any given treatment was the same for both soils, the total differed as a result of differences in the native levels. In every case the native nutrient content of the Waimea series was many times greater than for the Halii series.

When an account of a particular element in leachate, plant and soil is made, it turns out that the budget does

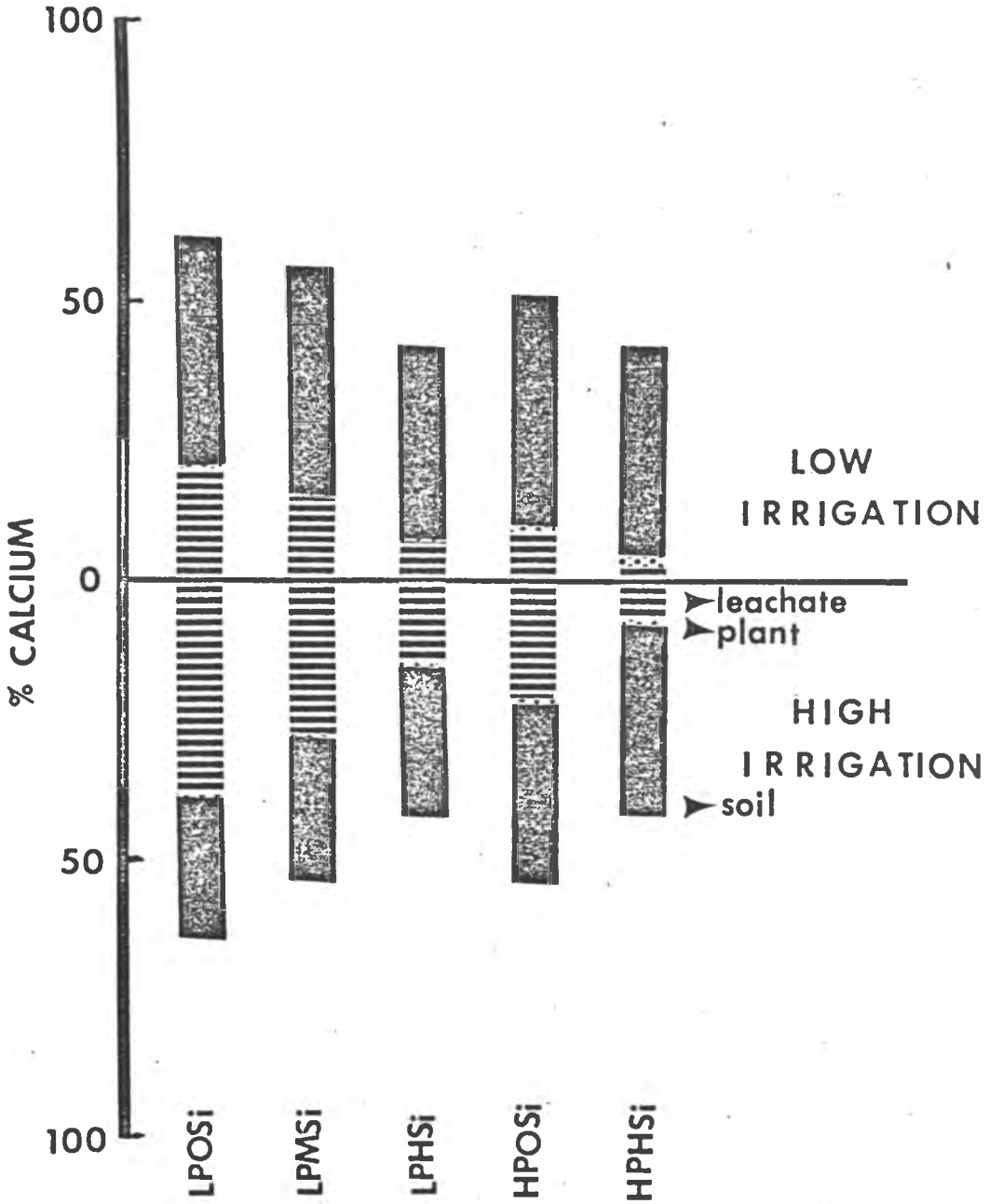

FIGURE 24. PERCENT DISTRIBUTION OF Ca IN LEACHATE, PLANT AND SOIL IN THE HALII SOIL

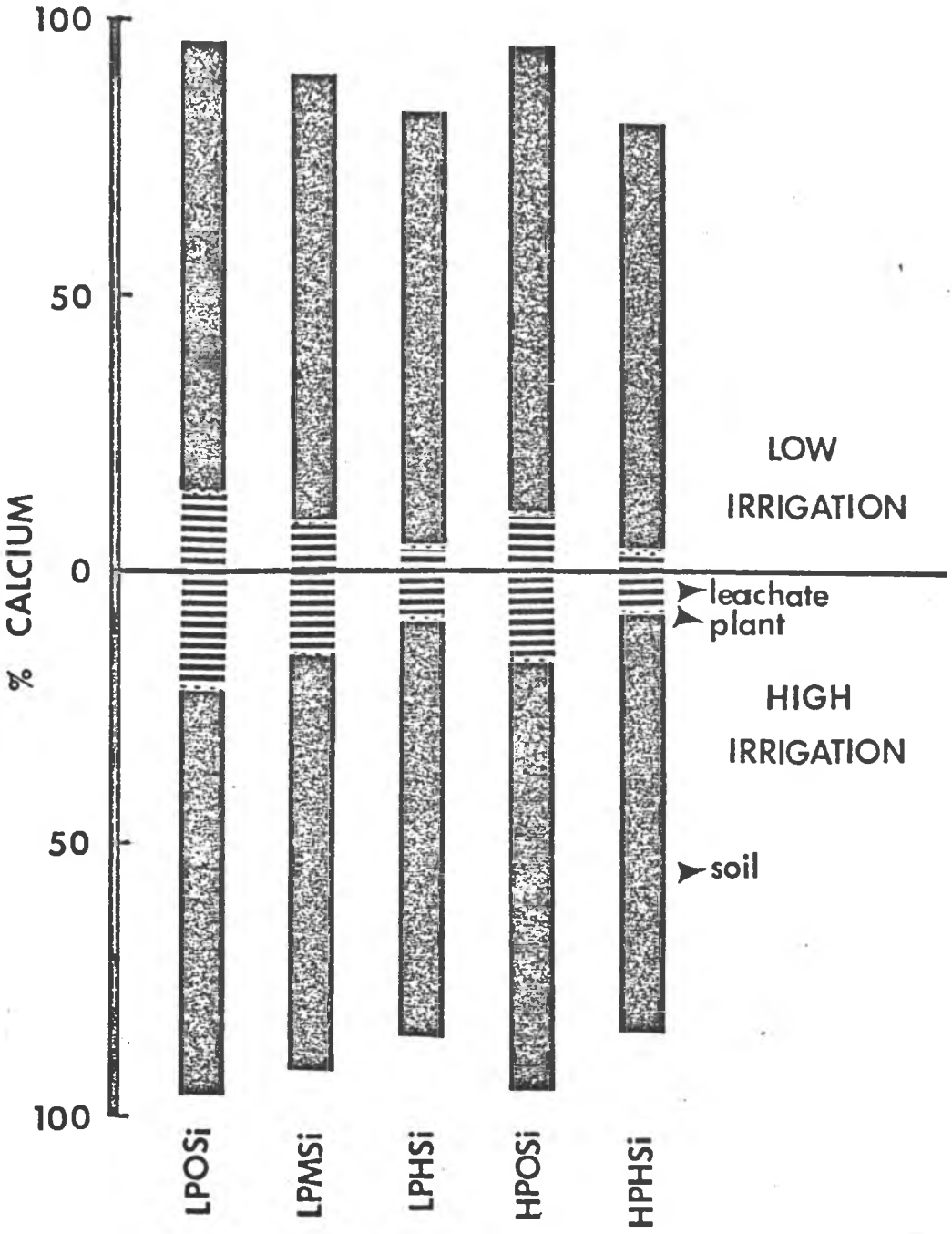

FIGURE 25. PERCENT DISTRIBUTION OF Ca IN LEACHATE, PLANT AND SOIL IN THE WAIMEA SOIL

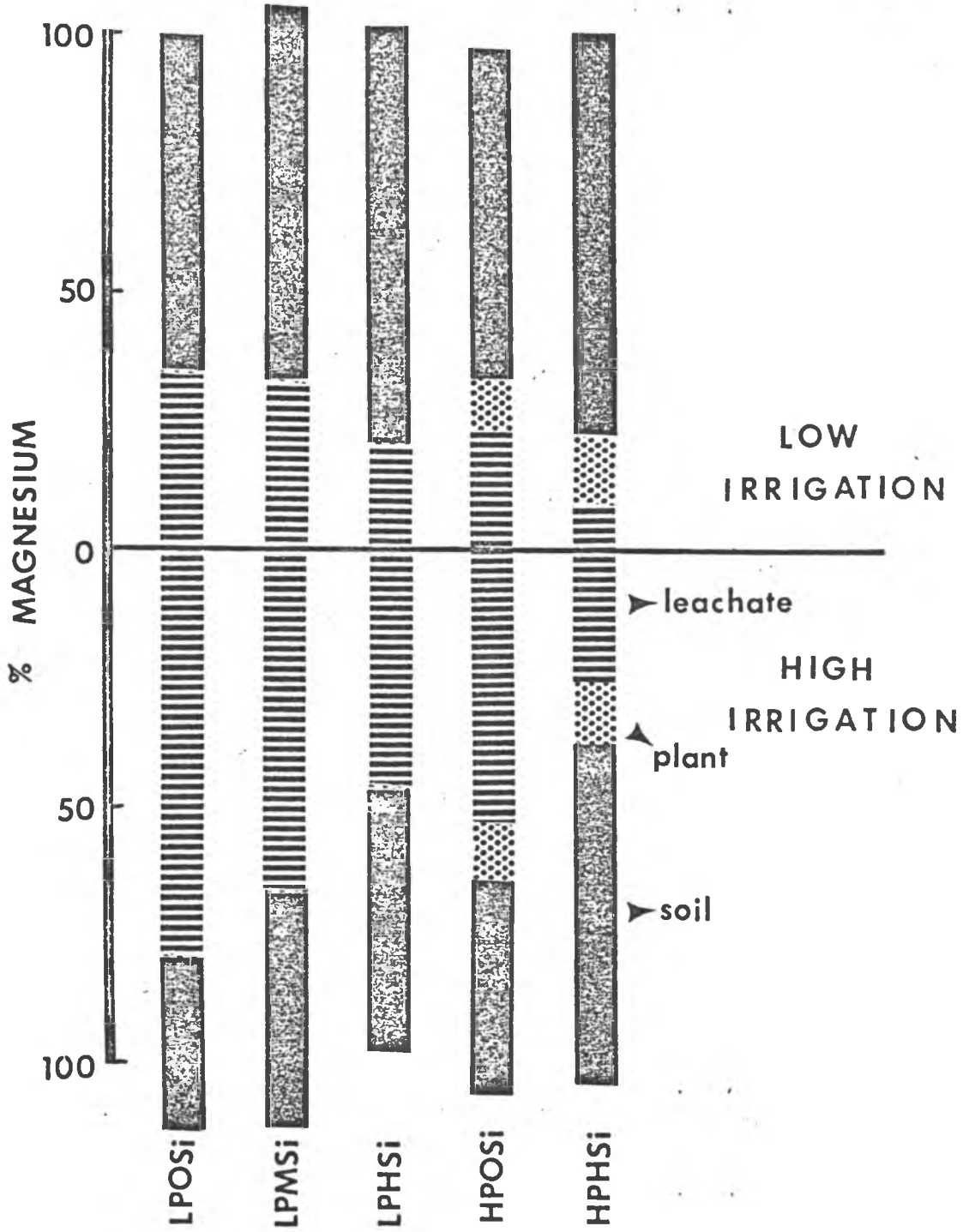

FIGURE 26. PERCENT DISTRIBUTION OF Mg IN LEACHATE, PLANT AND SOIL IN THE HALII SOIL

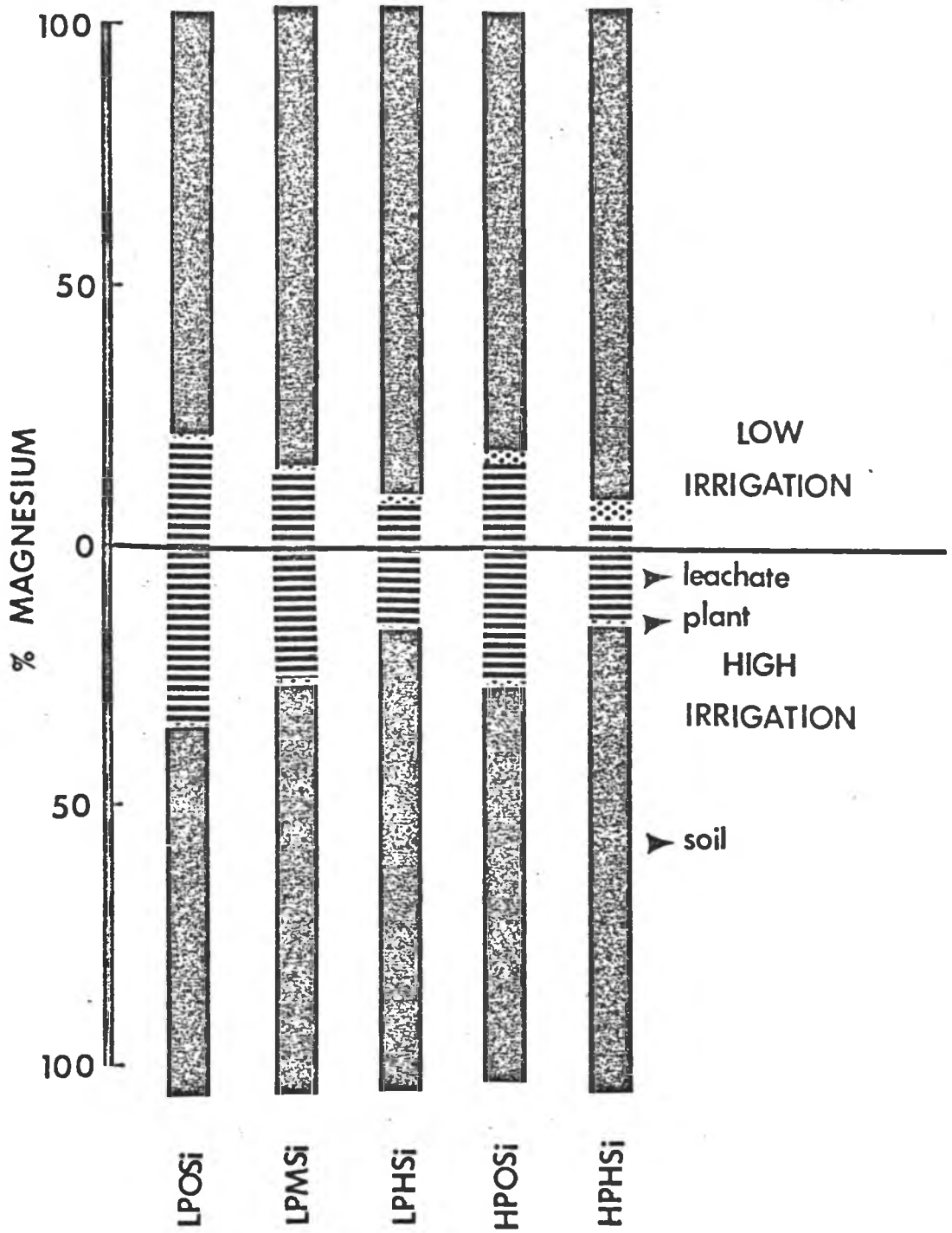

FIGURE 27. PERCENT DISTRIBUTION OF Mg IN LEACHATE, PLANT AND SOIL IN THE WAIMEA SOIL

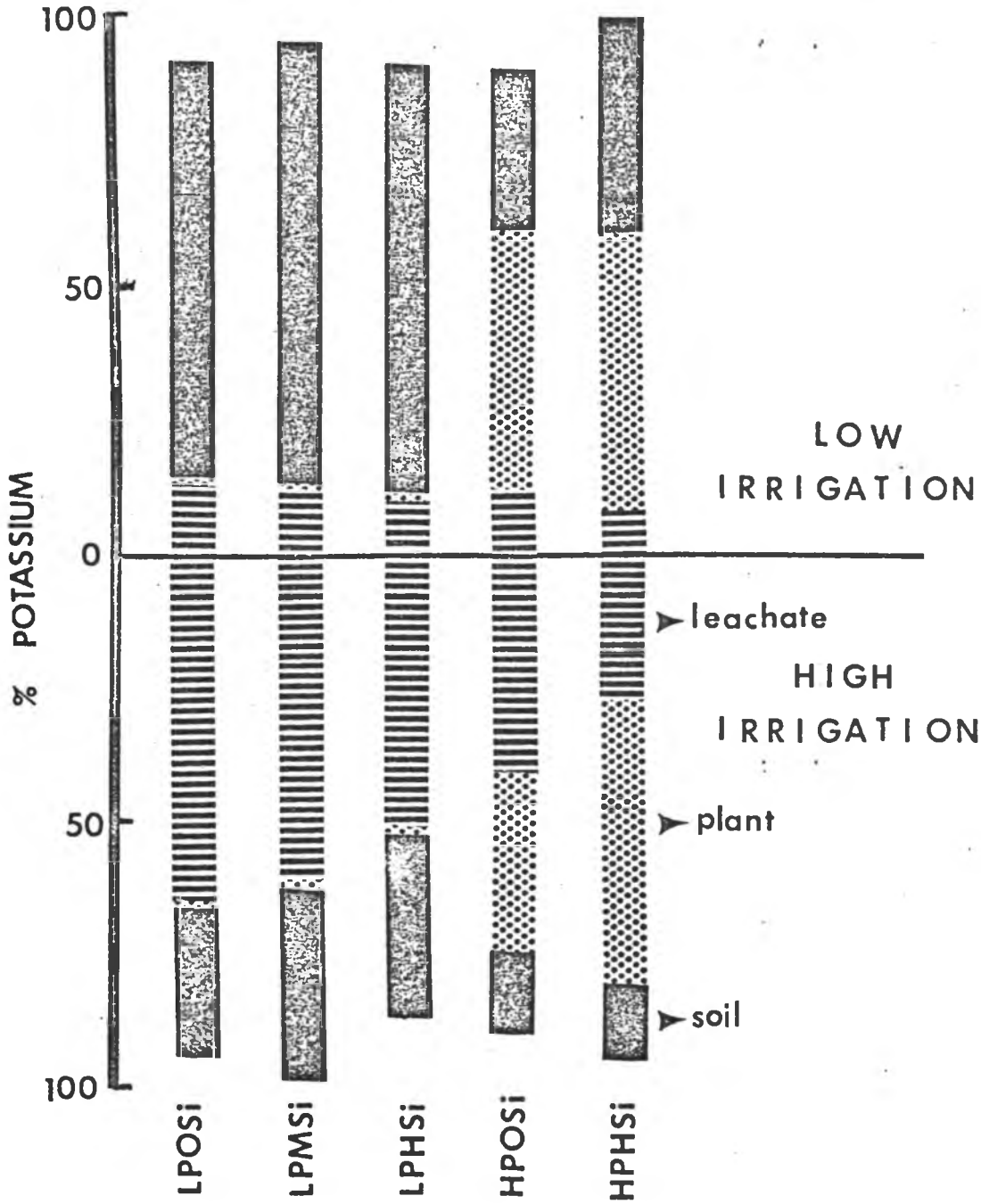

FIGURE 28. PERCENT DISTRIBUTION OF K IN LEACHATE, PLANT AND SOIL IN THE HALII SOIL

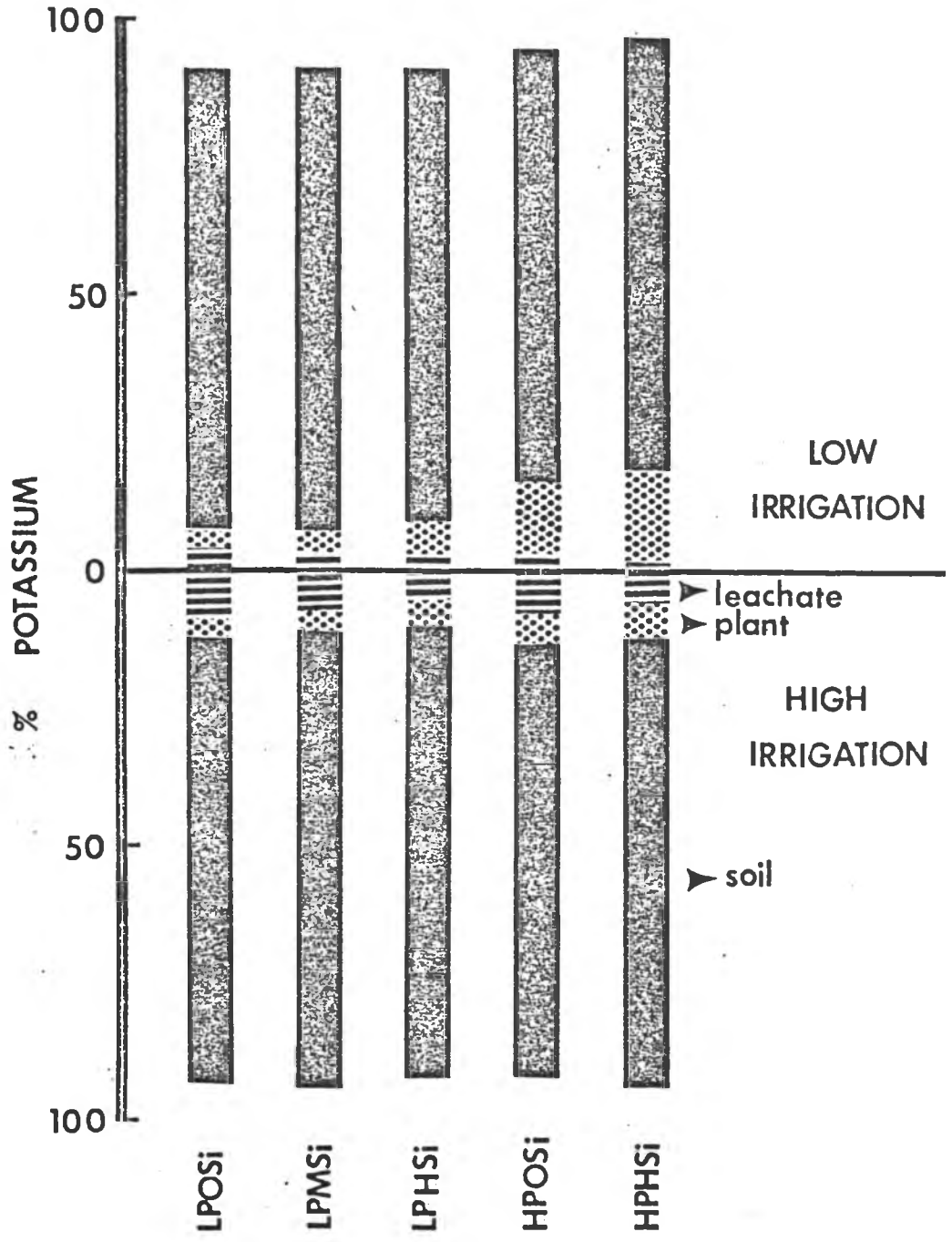

FIGURE 29. PERCENT DISTRIBUTION OF K IN LEACHATE, PLANT AND SOIL IN THE WAIMEA SOIL

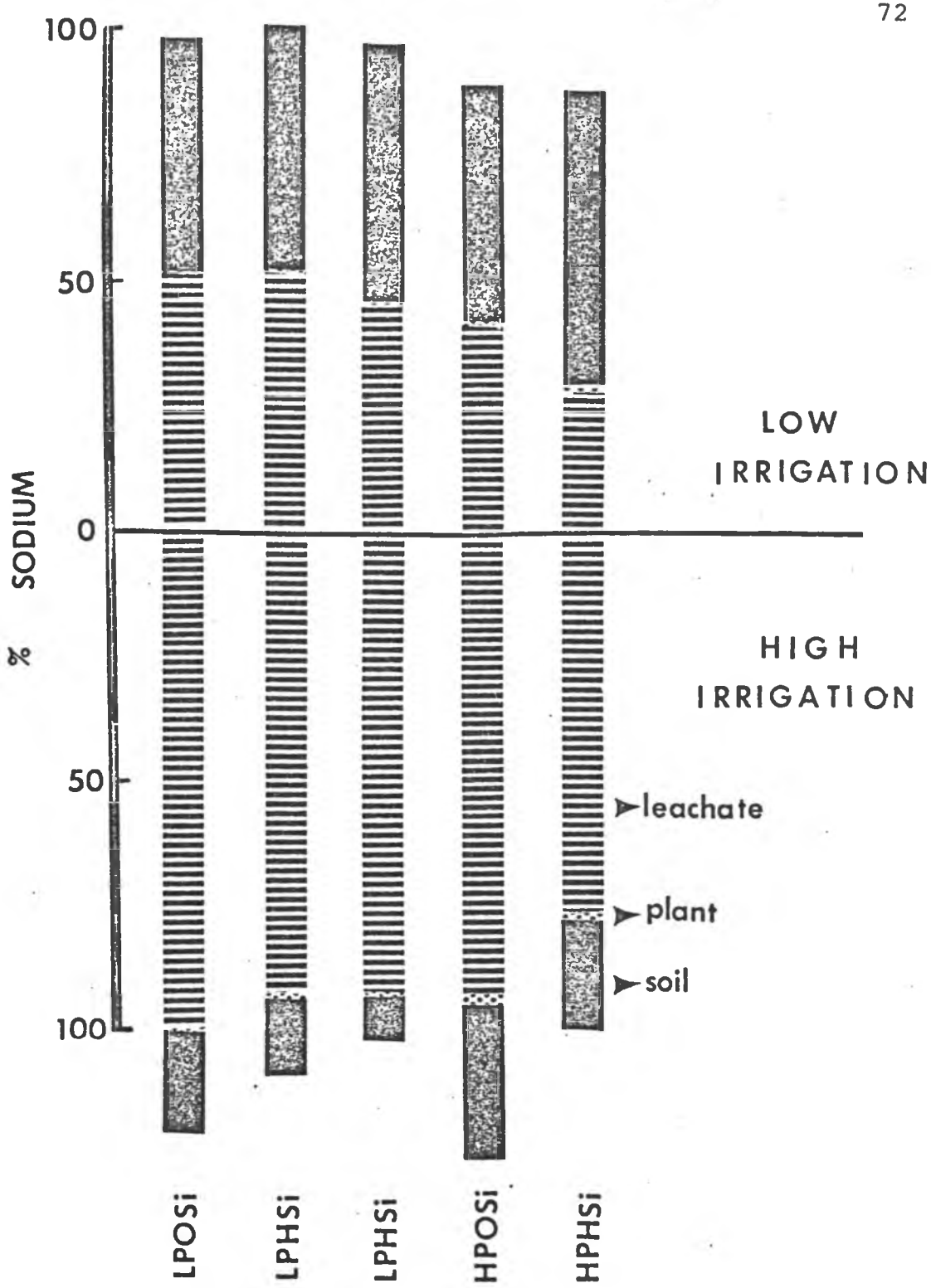

FIGURE 30. PERCENT DISTRIBUTION OF Na IN LEACHATE, PLANT AND SOIL IN THE HALII SOIL

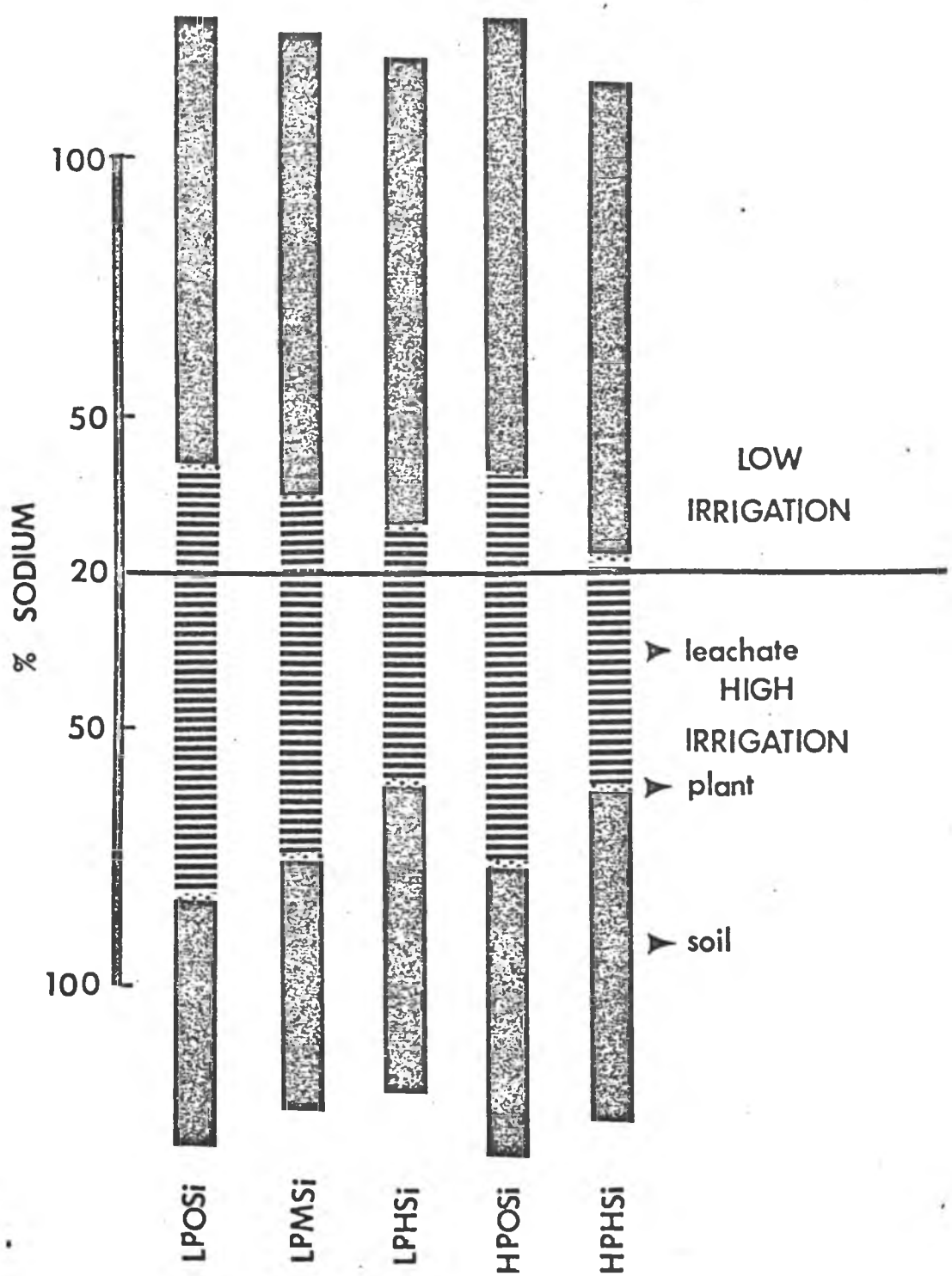

FIGURE 31. PERCENT DISTRIBUTION OF Na IN LEACHATE, PLANT AND SOIL IN THE WAIMEA SOIL

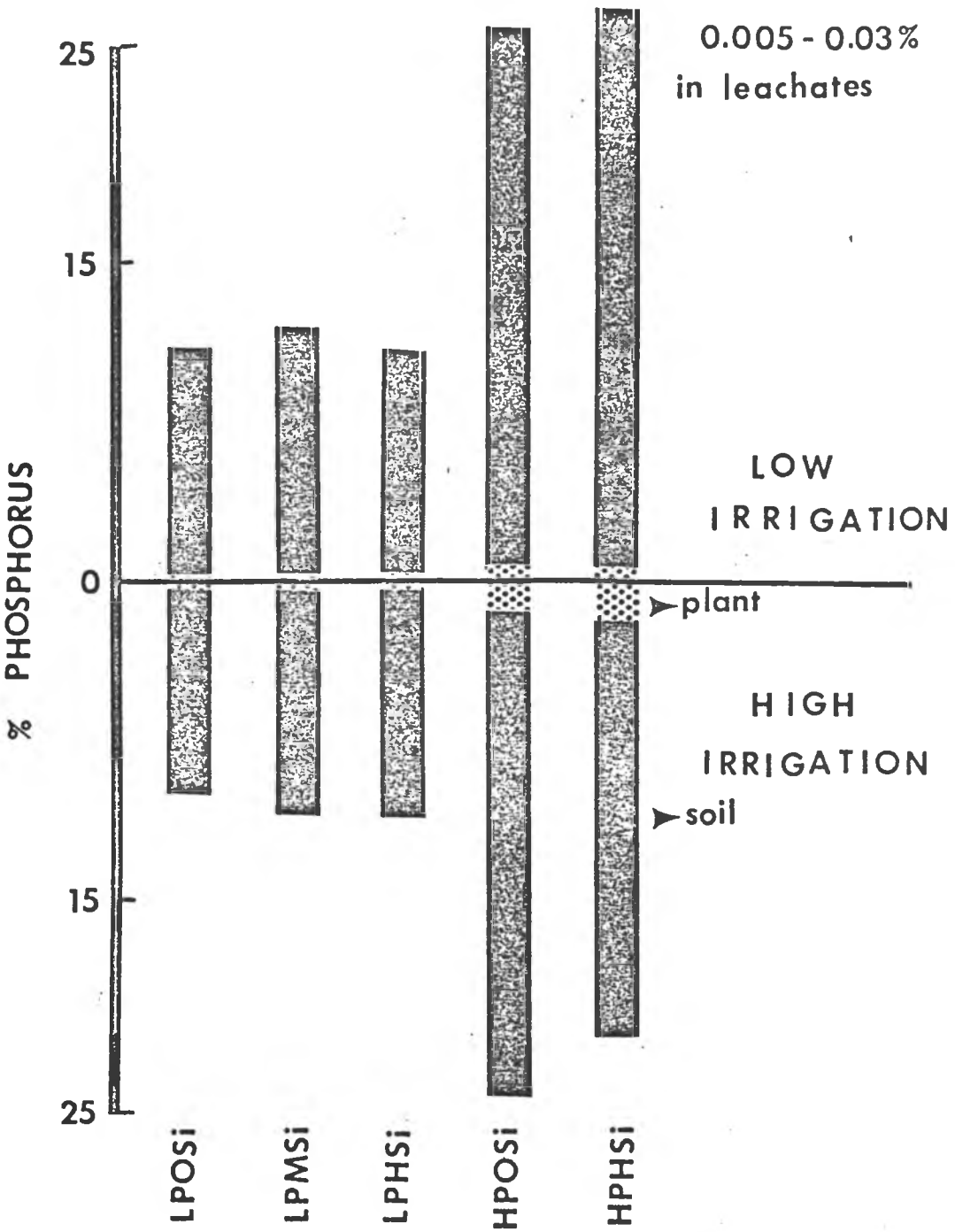

FIGURE 32. PERCENT DISTRIBUTION OF P IN LEACHATE, PLANT AND SOIL IN THE HALII SOIL

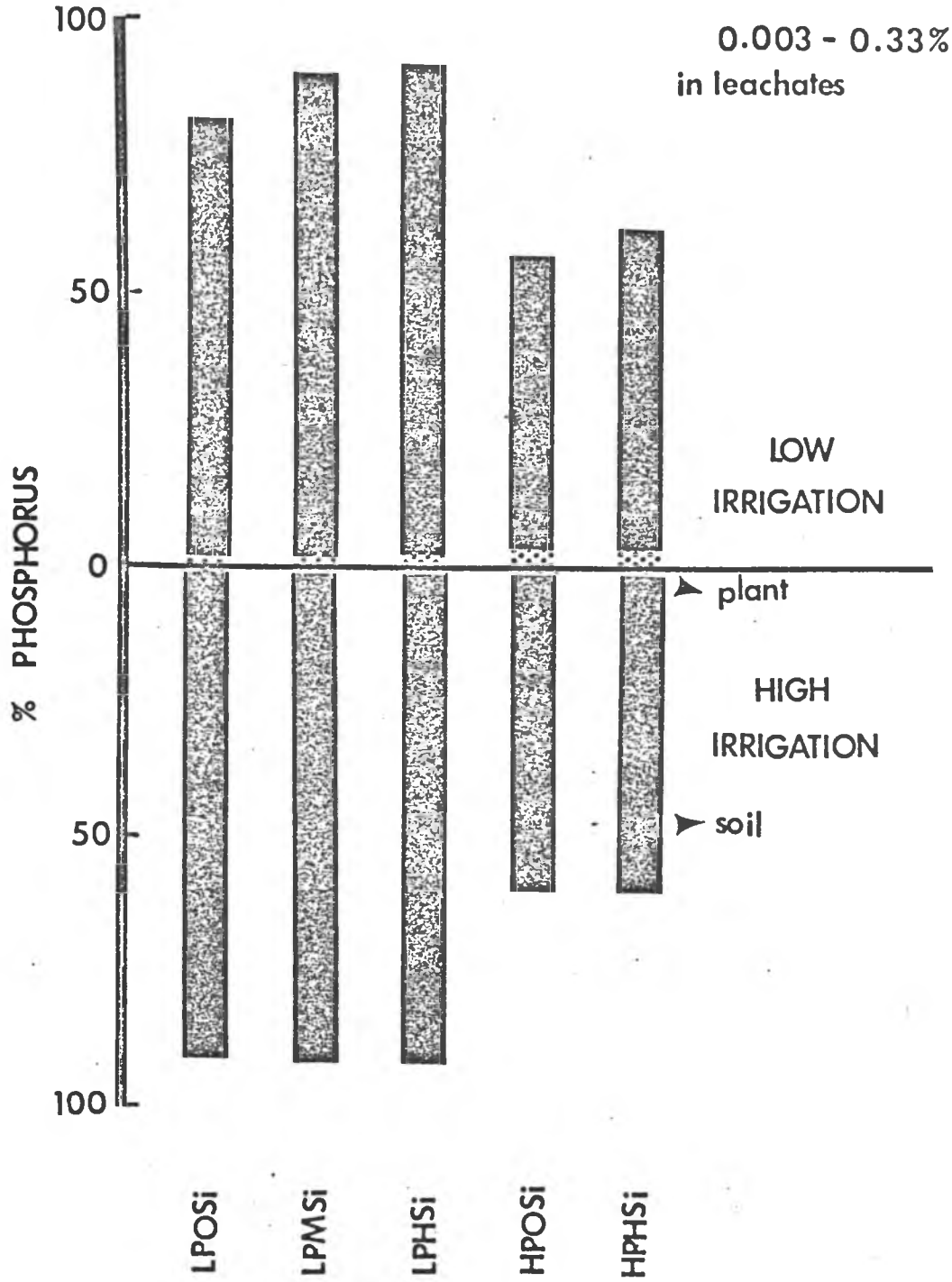

FIGURE 33. PERCENT DISTRIBUTION OF P IN LEACHATE, PLANT AND SOIL IN THE WAIMEA SOIL

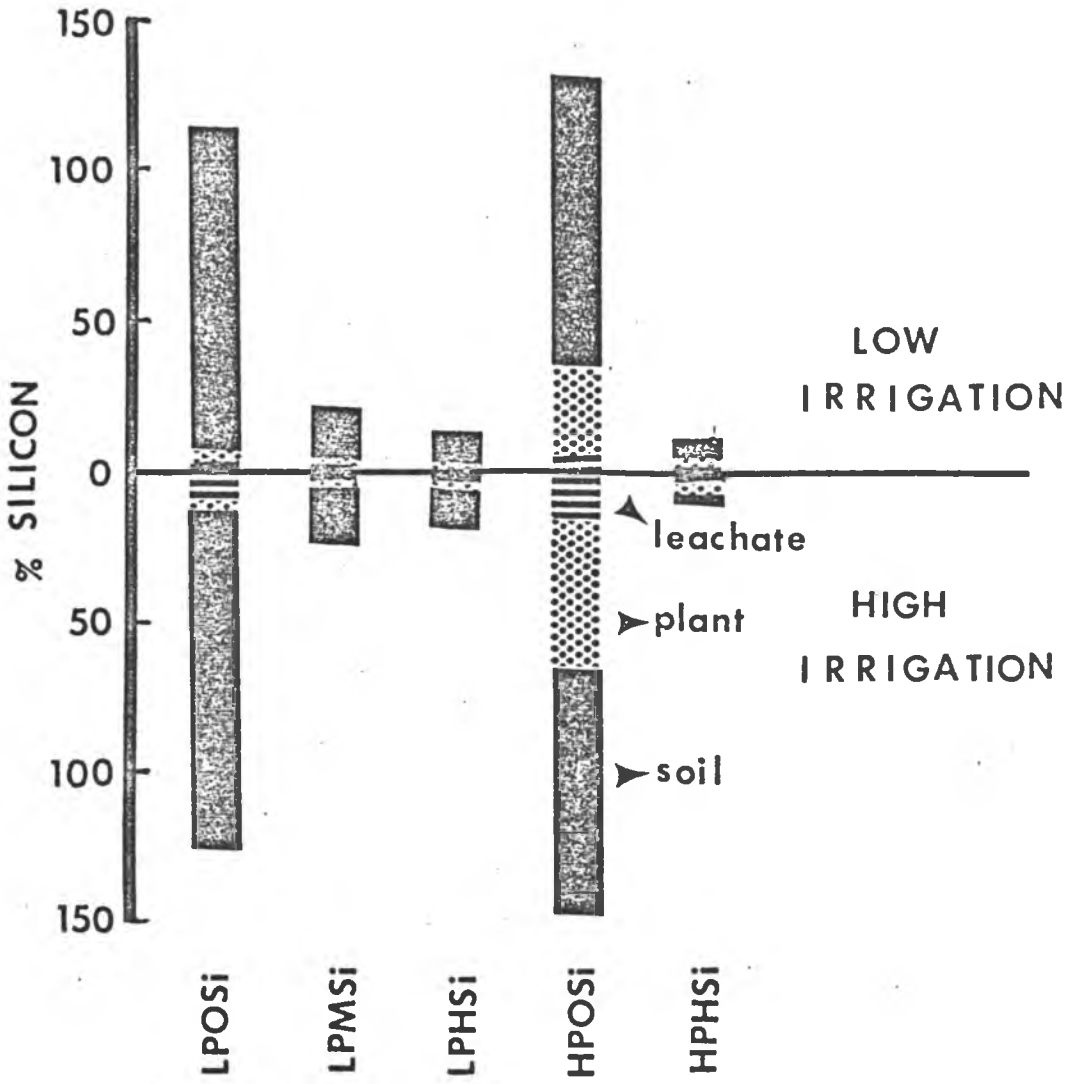

FIGURE 34. PERCENT DISTRIBUTION OF Si IN LEACHATE, PLANT AND SOIL IN THE HALII SOIL

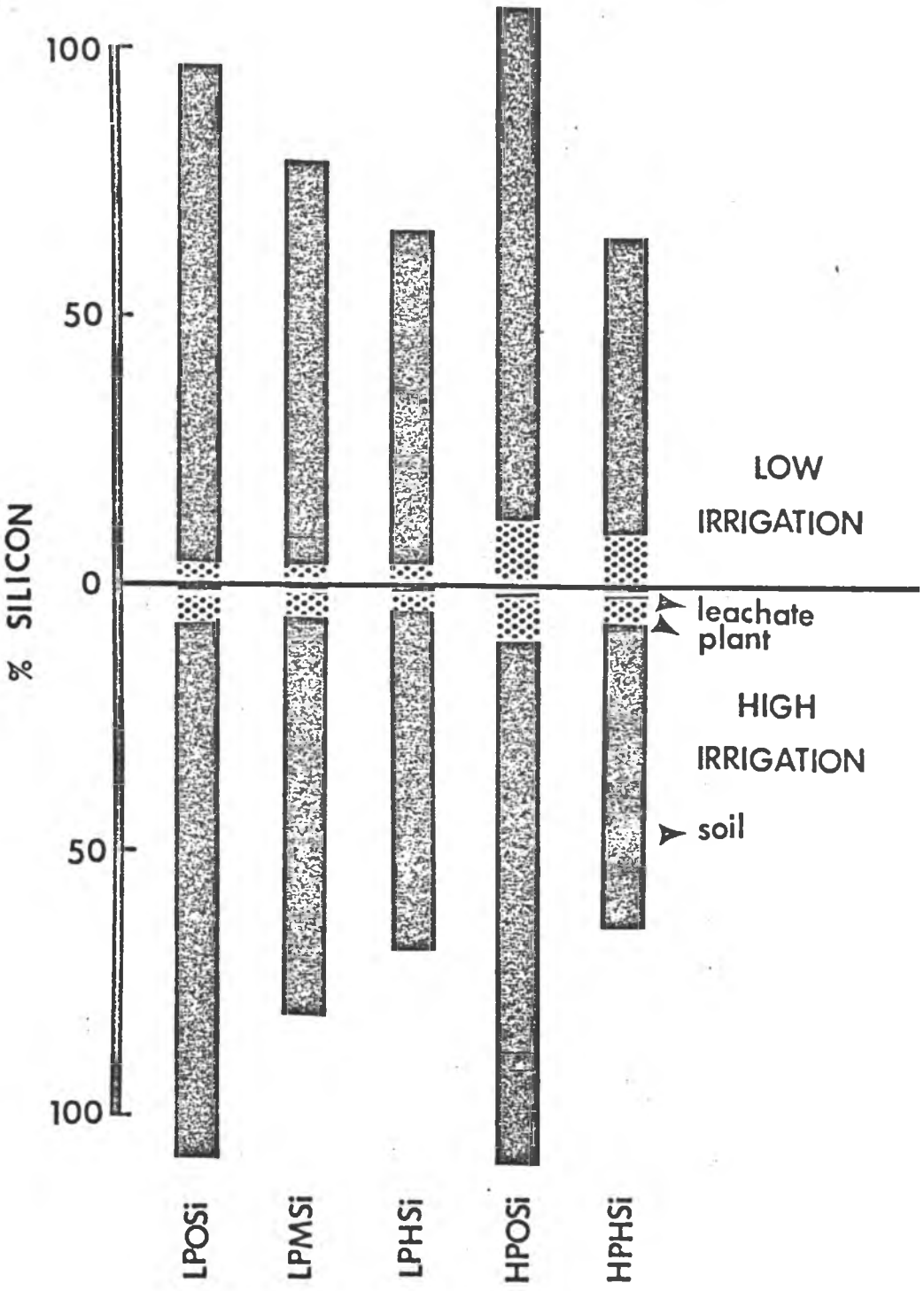

FIGURE 35. PERCENT DISTRIBUTION OF Si IN LEACHATE, PLANT AND SOIL IN THE WAIMEA SOIL

not always balance. In the case of Mg and K, the amounts measured in leachate, soil and plant fell within 10 percent of the native plus applied forms. In the case of sodium, the amount measured in leachate, soil and plant exceeded the amount initially present and added to the soil, by a substantial margin. The discrepancy can be attributed to impurities in the irrigation water, dust fall-out (the greenhouse was open on one side and adjacent to a roadway), release of non-exchangeable forms from soil and glassware and errors in laboratory methods.

In the case of Ca, the amount measured in leachate, plant and soil fell short of the initial value added or present in native forms. In the Halii soil as much as 58 percent of the Ca could not be accounted for. While Ca in the root was not included as part of the budget, one can readily show by approximation that consideration of roots would not alter the data significantly.

The fact that much of the Ca could not be accounted for is consistent with the findings of Mikami and Kimura (1964) who showed that the quantity of Ca recovered decreased as a function of time after liming. Their results are reproduced in Table V.

Purcell and Sun (1963) report that Ca adsorbed as an impurity on TiO_2 caused the zero point of charge of TiO_2 to shift to higher values. They claim that Ca was attracted to the negative surface by electrostatic and covalent forces.

TABLE V. FIXATION OF CALCIUM AS A FUNCTION OF TIME AFTER LIMING
(FROM MIKAMI AND KIMURA, 1964)

Soil	Soil Ca, ppm	Added Ca, ppm	Total Ca, ppm	1 Month		3 Months		5 Months	
				Recovered Ca, ppm	% Ca Fixed	Recovered Ca, ppm	% Ca Fixed	Recovered Ca, ppm	% Ca Fixed
Akaka (Hydrol Humic Latosol)	28	2,400	2,428	2,303	5.2	2,152	11.4	2,178	14.4
Manana (Humic Ferruginous Latosol)	18	800	818	822	-0.5	796	2.7	787	3.8
Lolekaa (Humic Latosol)	128	800	928	856	7.8	814	12.3	841	9.4

The Ca data in the Halii soil suggest that Ca may be specifically adsorbed ("fixed") in oxidic soils. In any case the amount of Ca which resists leaching, removal by plants or extraction by NH_4OAc is too large to be ignored.

While the amount of exchangeable Ca remained relatively constant, the amount leached decreased with increasing P or Si application, and the immobilized ("fixed") Ca increased with increasing P or Si. This relationship agrees with that of Purcell and Sun (1963) who state that "$CaCl_2$ rapidly reduces the negative potential but has no effect when the mineral is positively charged". Modi and Fuerstenau (1957) have similarly shown that Ba^{++} is specifically adsorbed on negatively charged alumina (αAl_2O_3) surface in aqueous suspensions. The case for specific adsorption of Ca in the Halii soil is strongly supported by the large amount of Ca which resists extraction by N-NH_4OAc. Specific adsorption of Ca is probably enhanced in buffered N-NH_4OAc solution since this solution has a higher pH than the soil.

The results of Ca data in the Halii soils suggest that Ca fixation may be a real and important phenomena in high oxide tropical soils. In the Waimea soil, the trend for specific adsorption of Ca was identical to that of the Halii but the magnitude of adsorption was smaller.

For oxidic tropical soils liming of negatively charged colloids of the variable charge type can lead to reduction

in CEC as demonstrated by Mikami and Kimura (1964). It is interesting to note that Mikami and Kimura added lime to an Akaka soil which contained colloids with net positive charge. The sign of the charge was verified by a measured positive $\triangle$pH value. Specific adsorption of Ca occurred in their sample when lime increased the soil pH above its zero point of charge. One can speculate that in an open system where leaching occur, specifically adsorbed Ca would gradually go into solution, thus providing a large source of this element to plants. The lack of plant response to Ca in acid tropical soils containing trace amounts of $\underline{N}$-NH_4OAc exchangeable Ca may be related to slow release of specifically adsorbed Ca.

If the hypothesis presented here regarding specific adsorption of Ca is correct, evidence for this should be contained in one or more of the numerous liming studies conducted in the State. The best evidence in support of this premise is found in the work of Rixon (1966).

The data in Table VI is a condensation of Table XI of Rixon's results. Rixon's data show that when no lime is added, CEC increase with increasing P application. This agrees with the findings of Mekaru and Uehara (1972). On the other hand when lime is applied in large quantities, CEC decreased and exchangeable Ca decreased with increasing P application; this case is consistent with the results of this thesis.

TABLE VI. CATION EXCHANGE, pH, EXCHANGEABLE CALCIUM FOR VARIOUS LIME AND PHOSPHATE LEVELS ADDED TO SOIL OF THE AKAKA SERIES (SUMMARIZED FROM RIXON, 1966)

Coral lb/acre	P_2O_5 lb/acre	pH	CEC	Exchangeable Ca me/100 gm
0	0	5.0	53.9	0.99
0	200	5.4	64.6	1.64
0	400	5.0	68.7	0.72
34,000	0	6.4	68.4	28.44
34,000	200	6.2	67.6	19.72
34,000	400	6.2	66.4	13.42

An equally good evidence in support of the operation of this mechanism in Hawaiian soils is found in the work of Mahilum, Fox and Silva (1969). The following data are taken from their publication:

Lime Added Tons/Acre	Ca Recovered In Excess of Check ($CaCO_3$ Equiv.) Tons/Acre
0.5	0.17
1.0	0.15
2.5	0.17
5.0	0.24

While these workers attributed the low recovery of applied lime to leaching, it is probable that in the light of the new data, their results can be better explained on the basis of specific adsorption of Ca.

It is not surprising that the best evidence in every case (Mikami and Kimura, 1964; Rixon, 1966; Mahilum etal, 1969), comes from work on the Akaka soil. This soil represents one of the most highly weathered members of a sequence of soils developed from volcanic ash on the Island of Hawaii. If the variable charge model operates in soils, it would do so in the Akaka series.

Although Mg is a divalent cation, there was no evidence of specific adsorption. Within the limits of experimental errors, all of the Mg could be accounted for in the leachate, plant and soil. Application of Si and/or

P increased the capacity of the soil to retain Mg and reduced leaching losses. The trends were similar in both soils.

Application of Si orP had similar effects on K as in Mg. The high irrigation treatment caused a large loss of K and Mg in the Halii soil. The greater loss in the high irrigation treatment in the Halii soil can be attributed to the fact that K and Mg were not specifically adsorbed and further to the fact that the Halii probably has a lower net negative charge.

The effect of irrigation treatment on cation leaching is most strongly expressed in the Na data. In fact, in view of the possible specific adsorption of Ca and the fact that monovalent cations are not known to be adsorbed in this manner, reclamation and management of saline oxidic soils may not only be different but easier compared to temperate region soils.

Phosphorus leached from both soils was too small to be represented graphically (Figures 32 and 33). As a result of P fixation, only a small fraction of the applied or native P could be recovered at the end of the experiment. In the Halii, a greater fraction of P was accounted for when P was applied in heavy doses. The opposite was true for the Waimea soil. This difference can be attributed to the fact that in the Halii soil, nearly all of the P applied at the low rate was fixed, whereas a

significant fraction of the P in the heavier application remained in extractable form.

The Si results (Figures 34 and 35) probably reflect the method of extraction from the soil rather than the actual situation in the soil. For the zero Si treatments, more than 100 percent of the total Si can be accounted for. When Si was applied at the rate of 484 or 968 ppm, only a small fraction of the total native and applied Si was recovered.

The low recovery is related to the fact that the Modified Truog method is designed to measure all of the Si in solutions but only part of the adsorbed Si. In short, it does not measure the full capacity factor for Si. To measure the full intensity and capacity factors, one may need to make many several extractions on a particular sample. This was not done in this work.

SUMMARY AND CONCLUSIONS

Two soils, one containing high amounts of iron and alumina oxide and another containing mostly amorphous aluminosilicate, were treated with two rates of phosphorus fertilizer, three rates of $CaSiO_3$ ammendment and two water application treatments and planted to sorghum. Calcium, magnesium and potassium levels were kept constant over all treatments for a given soil. A budget of Ca, K, Mg, Na, P and Si in leachate, plant and soil was kept.

Cation leaching decreased with increasing Si or P application indicating that addition of Si and P increases net negative charge on variable charge colloids. This effect was more pronounced in the oxide than in the amorphous aluminosilicate soil.

Cation concentration were generally higher in the larger plants, and therefore, total cation uptake was very high in those treatments which had large, healthy plants. The largest and healthiest plants were found in the high phosphorus treatments.

Retention of cations by the soil generally increased with increasing silicon or phosphorus application. In the special case of potassium, large uptake by plants in the high phosphorus treatment resulted in a reduced value retained by the soil.

In the Halii soil, about 50 percent of the calcium was specifically adsorbed and could not be extracted by $\underline{N}$-NH_4OAc.

The cation exchange capacity of the Halii soil decreased with increasing phosphorus application. This was attributed to neutralization of charge by specifically adsorbed calcium.

The results of this work give further evidence that a chemical model based on constant potential or variable charge colloid can be usefully applied to predict chemical behavior of high oxide soils.

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A P P E N D I X

TABLE VIIa. TOTAL Ca, K AND Mg (Mg/POT) IN LOW AND HIGH LEACHATES OF IRRIGATIONS [I + II + III + IV]. (MEANS OF 3 REPLICATES)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)			P-750 ppm (HP)		
			Ca	K	Mg	Ca	K	Mg
Waimea	(LW) 0.86	0	550.79	44.99	135.70	308.70	31.60	83.80
		484	288.03	34.87	89.78	--	--	--
		968	160.07	29.12	55.14	99.47	22.08	33.70
	(HW) 3.44	0	1,268.96	160.30	356.12	937.70	133.53	272.31
		484	919.33	133.96	266.73	--	--	--
		968	457.59	105.29	156.40	401.75	101.38	146.61
Halii	(LW) 0.86	0	316.50	8.27	21.10	200.23	11.39	20.23
		484	184.58	7.44	15.55	--	--	--
		968	86.10	5.99	9.85	43.25	6.49	6.07
	(HW) 3.44	0	963.67	129.81	78.65	579.94	107.11	55.66
		484	672.33	114.98	64.93	--	--	--
		968	348.38	90.77	45.14	183.46	67.86	26.45

TABLE VIIb. TOTAL Na, P AND Si IN LOW AND HIGH LEACHATES OF IRRIGATIONS [I + II + III + IV], (MG/POT EXCEPT P, UQ/POT: MEANS OF 3 REPLICATES)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)			P-750 ppm (HP)		
			Na	P	Si	Na	P	Si
Waimea	(LW) 0.86	0	19.66	5	3.25	14.75	139	3.44
		484	17.11	8	3.98	--	--	--
		968	15.37	13	4.87	11.78	164	4.72
	(HW) 3.44	0	63.42	35	17.12	56.64	1,010	21.94
		484	61.70	46	21.57	--	--	--
		968	52.45	85	25.18	54.79	1,407	29.94
Halii	(LW) 0.86	0	6.76	4	0.35	7.51	16	0.90
		484	7.77	3	1.47	--	--	--
		968	8.30	6	2.37	7.07	20	2.67
	(HW) 3.44	0	21.54	14	1.59	22.00	66	2.77
		484	26.62	15	7.77	--	--	--
		968	32.88	18	14.06	28.94	114	14.98

TABLE VIII. TOTAL WATER (ML/POT) LEACHED IN SUCCESSIVE IRRIGATION (MEANS OF 3 REPLICATES)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)					P-750 ppm (HP)				
			I+II	III+IV	V+VI	VII+VIII	Total	I+II	III+IV	V+VI	VII+VIII	Total
Waimea	(LW) 0.86	0	103	86	111	126	426	84	82	114	129	409
		484	91	85	115	109	400	--	--	--	--	--
		968	102	78	108	98	386	76	74	104	114	368
	(HW) 3.44	0	536	527	534	527	2,124	500	512	511	501	2,024
		484	528	519	490	526	2,063	--	--	--	--	--
		968	536	492	529	518	2,075	509	490	532	493	2,024
Halii	(LW) 0.86	0	90	76	109	122	397	99	90	170	132	491
		484	78	64	124	136	402	--	--	--	--	--
		968	72	57	118	131	378	78	61	176	138	453
	(HW) 3.44	0	454	528	545	551	2,078	455	555	519	515	2,044
		484	443	513	535	502	1,993	--	--	--	--	--
		968	437	509	511	548	2,005	427	497	520	509	1,953

TABLE IX. TOTAL Ca LEACHED (MG/POT) IN SUCCESSIVE IRRIGATIONS (MEANS OF 3 REPLICATES)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)				
			I+II	III+IV	V+VI	VII+VIII	Total
Waimea	(LW) 0.86	0	328.04	222.72	175.42	170.00	892.21
		484	152.20	135.83	125.25	112.33	525.61
		968	97.24	62.83	54.17	48.17	262.41
	(HW) 3.44	0	1,005.63	263.33	58.23	14.02	1,331.21
		484	660.00	259.33	41.07	12.30	972.70
		968	334.59	123.00	24.29	8.69	490.57
Halii	(LW) 0.86	0	168.75	147.75	162.32	148.25	627.07
		484	97.50	87.08	186.67	103.40	474.65
		968	45.00	41.10	72.58	72.33	231.01
	(HW) 3.44	0	567.92	395.75	172.28	82.06	1,218.01
		484	415.83	256.50	142.55	62.68	877.56
		968	191.57	156.81	81.28	37.14	466.80

TABLE IX. TOTAL Ca LEACHED (MG/POT) IN SUCCESSIVE IRRIGATIONS (MEANS OF 3 REPLICATES) (Continued)

Soil	cm H_2O per application	ppm Si	P-750 ppm (HP)				
			I+II	III+IV	V+VI	VII+VIII	Total
Waimea	(LW) 0.86	0	163.87	144.83	132.42	185.08	626.20
		484	--	--	--	--	--
		968	46.25	53.22	37.44	25.62	162.53
	(HW) 3.44	0	726.62	211.08	46.84	24.45	1,009.01
		484	--	--	--	--	--
		968	276.25	125.50	17.98	9.85	429.58
Halii	(LW) 0.86	0	107.02	93.21	52.23	21.32	273.78
		484	--	--	--	--	--
		968	21.45	21.80	34.67	14.19	92.11
	(HW) 3.44	0	325.06	254.88	56.19	19.96	656.09
		484	--	--	--	--	--
		968	92.63	90.83	27.75	8.58	219.79

TABLE X. TOTAL K LEACHED (MG/POT) IN SUCCESSIVE IRRIGATIONS (MEANS OF 3 REPLICATES)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)				
			I+II	III+IV	V+VI	VII+VIII	Total
Waimea	(LW) 0.86	0	24.84	20.15	21.75	21.71	88.45
		484	16.78	18.09	18.04	16.57	69.48
		968	15.48	13.64	12.87	10.46	52.45
	(HW) 3.44	0	97.88	62.42	25.93	12.65	198.88
		484	85.62	48.34	19.09	10.70	163.75
		968	64.40	40.89	15.72	10.38	131.39
Halii	(LW) 0.86	0	2.89	5.38	13.31	15.32	36.90
		484	3.51	3.93	12.58	17.81	37.83
		968	2.49	3.50	9.85	14.18	30.02
	(HW) 3.44	0	48.96	80.85	46.39	24.87	201.87
		484	46.90	68.08	48.08	27.23	190.29
		968	36.42	54.35	40.47	25.46	156.70

TABLE X. TOTAL K LEACHED (MG/POT) IN SUCCESSIVE IRRIGATIONS (MEANS OF 3 REPLICATES) (Continued)

Soil	cm H_2O per application	ppm Si	P-750 ppm (HP)				
			I+II	III+IV	V+VI	VII+VIII	Total
Waimea	(LW) 0.86	0	16.32	15.28	20.52	19.98	72.10
		484	--	--	--	--	--
		968	9.96	12.12	10.08	8.02	40.18
	(HW) 3.44	0	81.33	52.20	21.17	13.54	168.24
		484	--	--	--	--	--
		968	65.44	35.94	15.41	9.68	126.47
Halii	(LW) 0.86	0	5.44	5.95	15.96	9.34	36.69
		484	--	--	--	--	--
		968	3.13	3.36	13.55	6.63	26.67
	(HW) 3.44	0	43.97	63.14	15.39	3.51	126.01
		484	--	--	--	--	--
		968	27.27	40.59	13.66	3.60	85.12

TABLE XI. TOTAL Mg LEACHED (MG/POT) IN SUCCESSIVE IRRIGATIONS (MEANS OF 3 REPLICATES)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)				
			I+II	III+IV	V+VI	VII+VIII	Total
Waimea	(LW) 0.86	0	76.67	59.03	44.17	46.63	226.50
		484	45.55	44.23	36.55	35.18	161.51
		968	31.72	23.42	19.50	16.36	91.00
	(HW) 3.44	0	277.12	79.00	15.23	4.04	375.39
		484	202.34	64.39	12.40	3.16	282.29
		968	107.20	49.20	7.93	2.78	167.11
Halii	(LW) 0.86	0	10.51	10.59	11.30	11.44	43.84
		484	7.62	7.93	13.91	11.82	41.28
		968	5.26	4.59	7.85	8.35	26.05
	(HW) 3.44	0	46.99	31.66	15.46	6.76	100.87
		484	36.80	28.13	14.26	6.35	85.54
		968	24.78	20.36	10.22	4.88	60.24

TABLE XI. TOTAL Mg LEACHED (MG/POT) IN SUCCESSIVE IRRIGATIONS (MEANS OF 3 REPLICATES) (Continued)

Soil	cm H_2O per application	ppm Si	P-750 ppm (HP)				
			I+II	III+IV	V+VI	VII+VIII	Total
Waimea	(LW) 0.86	0	45.60	38.20	37.85	59.28	180.93
		484	--	--	--	--	--
		968	16.13	17.57	11.93	9.12	54.75
	(HW) 3.44	0	208.72	63.59	11.93	5.53	289.77
		484	--	--	--	--	--
		968	101.87	44.74	7.12	2.81	156.54
Halii	(LW) 0.86	0	9.04	11.19	6.20	2.97	29.40
		484	--	--	--	--	--
		968	3.13	2.94	3.96	1.90	11.93
	(HW) 3.44	0	33.17	22.49	6.05	2.10	63.81
		484	--	--	--	--	--
		968	12.31	14.14	4.48	1.20	32.13

TABLE XII. TOTAL Na LEACHED (MG/POT) IN SUCCESSIVE IRRIGATIONS (MEANS OF 3 REPLICATES)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)					P-750 ppm (HP)				
			I+II	III+IV	V+VI	VII+VIII	Total	I+II	III+IV	V+VI	VII+VIII	Total
Waimea	(LW) 0.86	0	11.08	8.58	8.28	9.37	37.31	8.06	6.69	8.09	14.12	36.96
		484	8.56	8.55	8.85	9.04	35.00	--	--	--	--	--
		968	9.00	6.37	8.34	7.51	31.22	5.70	6.08	5.78	6.74	24.30
	(HW) 3.44	0	42.90	20.52	9.27	4.56	77.25	36.42	20.22	9.04	5.35	71.03
		484	40.12	21.58	9.06	5.10	75.86	--	--	--	--	--
		968	32.15	20.30	9.00	5.72	67.17	36.00	18.79	8.53	5.09	68.41
Halii	(LW) 0.86	0	3.41	3.35	3.83	3.73	14.32	3.55	3.96	2.85	1.11	11.47
		484	4.08	3.69	7.34	4.01	19.12	--	--	--	--	--
		968	4.33	3.97	6.35	5.98	20.63	3.75	3.34	3.47	2.37	12.93
	(HW) 3.44	0	12.40	9.14	4.66	1.65	27.85	12.18	9.82	2.59	1.05	25.64
		484	16.36	10.26	5.17	2.34	34.13	--	--	--	--	--
		968	20.42	12.46	6.32	3.06	42.26	16.17	12.77	3.96	2.23	35.13

TABLE XIII. TOTAL P LEACHED (UG/POT) IN SUCCESSIVE IRRIGATIONS (MEANS OF 3 REPLICATES)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)					P-750 ppm (HP)				
			I+II	III+IV	V+VI	VII+VIII	Total	I+II	III+IV	V+VI	VII+VIII	Total
Waimea	(LW) 0.86	0	3	2	2	3	10	69	70	42	41	222
		484	4	4	4	10	22	--	--	--	--	--
		968	9	4	7	18	38	95	69	69	127	360
	(HW) 3.44	0	17	18	28	58	121	522	488	540	715	2,265
		484	26	20	29	78	153	--	--	--	--	--
		968	40	45	56	117	258	712	695	956	1,012	3,375
Halii	(LW) 0.86	0	3	1	1	0	5	8	8	19	36	71
		484	1	2	1	2	6	--	--	--	--	--
		968	4	2	2	2	10	13	7	27	27	74
	(HW) 3.44	0	8	6	2	0	16	32	34	43	112	221
		484	6	9	0	0	15	--	--	--	--	--
		968	7	11	1	0	19	63	51	80	159	353

TABLE XIV. TOTAL Si LEACHED (MG/POT) IN SUCCESSIVE IRRIGATIONS (MEANS OF 3 REPLICATES)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)					P-750 ppm (HP)				
			I+II	III+IV	V+VI	VII+VIII	Total	I+II	III+IV	V+VI	VII+VIII	Total
Waimea	(LW) 0.86	0	1.73	1.52	1.88	2.46	7.59	1.90	1.54	2.36	2.51	8.31
		484	2.00	1.98	2.35	2.49	8.82	--	--	--	--	--
		968	2.73	2.14	2.42	2.26	9.55	2.29	2.43	2.46	2.99	10.17
	(HW) 3.44	0	8.79	8.33	8.46	8.43	34.01	10.89	11.05	9.36	9.26	40.56
		484	11.08	10.49	9.29	10.16	41.02	--	--	--	--	--
		968	13.28	11.90	11.63	11.46	48.27	15.48	14.46	13.35	12.71	56.00
Halii	(LW) 0.86	0	0.19	0.16	0.30	0.23	0.88	0.45	0.45	0.27	0.24	1.41
		484	0.78	0.69	1.20	1.45	4.12	--	--	--	--	--
		968	1.27	1.10	1.99	2.47	6.83	1.50	1.17	1.07	0.98	4.72
	(HW) 3.44	0	0.80	0.79	0.59	0.81	2.99	1.41	1.36	0.73	0.76	4.26
		484	3.37	4.40	4.38	4.05	16.20	--	--	--	--	--
		968	6.59	7.47	7.20	7.89	29.15	7.07	7.91	3.84	2.91	21.73

TABLE XV. YIELD OF OVEN DRIED PLANT TOPS AND ROOTS (MEANS OF 3 REPLICATES)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)		P-750 ppm (HP)	
			Tops	Roots	Tops	Roots
Waimea	(LW) 0.86	0	1.98	0.65	7.73	1.88
		484	2.41	0.85	--	--
		968	4.00	1.26	8.38	2.18
	(HW) 3.44	0	2.48	0.96	4.01	1.51
		484	2.76	1.14	--	--
		968	2.78	1.02	4.09	1.41
Halii	(LW) 0.86	0	0.25	0.12	3.49	1.38
		484	0.22	0.15	--	--
		968	0.33	0.23	4.32	1.48
	(HW) 3.44	0	0.23	0.15	5.16	2.07
		484	0.25	0.15	--	--
		968	0.29	0.27	6.09	2.21

TABLE XVIa. CONCENTRATION OF Ca, K AND Mg IN PLANT TOPS.
(MEANS OF 3 REPLICATES)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)			P-750 ppm (HP)		
			% Ca	% K	ppm Mg	% Ca	% K	ppm Mg
Waimea	(LW) 0.86	0	0.75	3.20	3,814	0.58	3.38	4,141
		484	0.66	3.27	3,522	--	--	--
		968	0.53	3.21	3,522	0.51	4.12	4,673
	(HW) 3.44	0	0.36	3.98	1,649	0.37	2.86	1,855
		484	0.34	2.86	1,597	--	--	--
		968	0.34	2.98	1,787	0.34	3.03	2,027
Halii	(LW) 0.86	0	0.79	1.46	2,422	0.73	4.30	3,728
		484	0.75	1.08	2,543	--	--	--
		968	0.65	1.60	2,577	0.59	3.67	3,952
	(HW) 3.44	0	0.66	1.82	2,526	0.48	2.19	2,663
		484	0.61	2.09	2,354	--	--	--
		968	0.67	2.11	2,485	0.44	2.69	2,869

TABLE XVIb. CONCENTRATION OF Na, P AND Si IN PLANT TOPS
(MEANS OF 3 REPLICATES)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)			P-750 ppm (HP)		
			ppm Na	ppm P	% Si	ppm Na	ppm P	% Si
Waimea	(LW) 0.86	0	105	2,134	1.63	83	3,721	1.56
		484	103	1,659	1.77	--	--	--
		968	103	1,649	1.54	101	4,277	2.11
	(HW) 3.44	0	86	2,052	2.19	91	3,077	2.16
		484	94	1,970	2.25	--	--	--
		968	96	2,199	2.51	94	3,223	2.61
Halii	(LW) 0.86	0	187	725	0.45	107	1,810	0.24
		484	215	870	1.36	--	--	--
		968	190	771	1.86	110	1,672	0.80
	(HW) 3.44	0	191	703	0.26	106	1,665	0.28
		484	168	893	1.48	--	--	--
		968	179	794	1.99	105	1,749	1.03

TABLE XVII. EXCHANGEABLE CATIONS, TOTAL CATIONS, CEC (ME/100 GM) AND IN PARENTHESIS, PERCENT BASE SATURATION (MEANS OF 3 REPLICATES)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)						P-750 ppm (HP)					
			Ca	K	Mg	Na	Total	CEC	Ca	K	Mg	Na	Total	CEC
Waimea	(LW) 0.86	0	26.00	4.62	7.43	0.34	38.39 (72.33)	53.07	26.83	4.36	7.51	0.35	39.05 (73.88)	52.85
		484	26.00	4.62	8.07	0.40	39.09 (73.81)	52.96	--	--	--	--	--	--
		968	24.83	4.53	8.51	0.44	38.31 (70.50)	54.34	25.83	4.36	8.59	0.45	39.23 (74.52)	52.64
	(HW) 3.44	0	23.83	4.45	6.50	0.20	34.98 (64.81)	53.97	25.17	4.36	6.96	0.24	36.73 (64.79)	56.69
		484	24.00	4.53	7.24	0.23	36.00 (64.60)	55.72	--	--	--	--	--	--
		968	24.67	4.53	8.15	0.30	37.65 (68.81)	54.71	24.50	4.53	8.23	0.32	37.58 (66.56)	56.46
Halii	(LW) 0.86	0	6.37	0.62	0.69	0.06	7.74 (22.68)	34.12	6.40	0.26	0.68	0.08	7.42 (24.70)	30.03
		484	5.93	0.65	0.78	0.08	7.44 (22.04)	33.75	--	--	--	--	--	--
		968	5.43	0.64	0.86	0.10	7.03 (20.73)	33.91	5.90	0.23	0.83	0.11	7.07 (23.28)	30.36
	(HW) 3.44	0	3.87	0.23	0.38	0.03	4.51 (13.03)	34.60	5.00	0.12	0.45	0.09	5.66 (18.48)	30.62
		484	4.00	0.28	0.49	0.02	4.79 (13.95)	34.33	--	--	--	--	--	--
		968	4.17	0.28	0.54	0.02	5.01 (14.70)	34.07	5.30	0.12	0.70	0.05	6.17 (20.36)	30.30

TABLE XVIII. RESIDUAL EXTRACTABLE P (ppm) AND Si (ppm) FROM HALII AND WAIMEA SOIL (MEANS OF 3 REPLICATES)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)		P-750 ppm (HP)	
			P	Si	P	Si
Waimea	(LW) 0.86	0	310	1,123	558	1,167
		484	338	1,284	--	--
		968	344	1,364	604	1,235
	(HW) 3.44	0	342	1,207	600	1,179
		484	344	1,263	--	--
		968	345	1,377	608	1,242
Halii	(LW) 0.86	0	11	31	184	28
		484	12	107	--	--
		968	11	144	170	84
	(HW) 3.44	0	10	33	168	24
		484	11	108	--	--
		968	11	153	149	78

TABLE XIX. pH IN H_2O, KCl AND KNO_3 PASTES AND ΔpH
(MEANS OF 3 REPLICATES)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)					P-750 ppm (HP)				
			H_2O	KCl	pH_{KCl}	KNO_3	pH_{KNO_3}	H_2O	KCl	pH_{KCl}	KNO_3	pH_{KNO_3}
Waimea	(LW) 0.86	0	5.78	5.21	-0.57	5.38	-0.40	6.02	5.30	-0.72	5.41	-0.61
		484	5.97	5.37	-0.60	5.39	-0.58	--	--	--	--	--
		968	6.10	5.34	-0.76	5.42	-0.68	6.03	5.16	-0.87	5.38	-0.65
	(HW) 3.44	0	6.28	5.34	-0.94	5.28	-1.00	6.10	5.27	-0.83	5.21	-0.89
		484	6.22	5.31	-0.91	5.29	-0.93	--	--	--	--	--
		968	6.32	5.37	-0.95	5.37	-0.95	6.09	5.19	-0.90	5.34	-0.75
Halii	(LW) 0.86	0	4.75	4.63	-0.12	4.59	-0.16	5.10	4.60	-0.50	4.72	-0.38
		484	4.80	4.62	-0.18	4.68	-0.12	--	--	--	--	--
		968	4.83	4.61	-0.22	4.64	-0.19	4.98	4.65	-0.33	4.66	-0.32
	(HW) 3.44	0	4.98	4.73	-0.25	4.73	-0.26	5.25	4.67	-0.58	4.70	-0.55
		484	5.00	4.69	-0.31	4.71	-0.29	--	--	--	--	--
		968	5.12	4.76	-0.36	4.78	-0.34	5.31	4.67	-0.64	4.75	-0.56

TABLE XX. pH IN H_2O, KCl AND KNO_3 1:5 DILUTIONS AND ΔpH
(MEANS OF 3 REPLICATES)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)					P-750 ppm (HP)				
			H_2O	KCl	pH_{KCl}	KNO_3	pH_{KNO_3}	H_2O	KCl	pH_{KCl}	KNO_3	pH_{KNO_3}
Waimea	(LW) 0.86	0	6.27	5.56	-0.71	5.67	-0.60	6.24	5.56	-0.68	5.53	-0.71
		484	6.48	5.61	-0.87	5.64	-0.84	--	--	--	--	--
		968	6.77	5.71	-1.06	5.81	-0.96	6.70	5.73	-0.97	5.61	-1.09
	(HW) 3.44	0	6.63	5.60	-1.03	5.65	-0.98	6.49	5.47	-1.01	5.47	-1.02
		484	6.71	5.61	-1.10	5.72	-0.95	--	--	--	--	--
		968	6.88	5.74	-1.13	5.70	-1.18	6.65	5.57	-1.08	5.54	-1.11
Halii	(LW) 0.86	0	5.11	4.89	-0.22	4.82	-0.29	5.61	4.99	-0.62	4.93	-0.68
		484	5.34	4.83	-0.51	4.85	-0.49	--	--	--	--	--
		968	5.38	5.03	-0.35	4.84	-0.54	5.70	5.00	-0.70	4.87	-0.83
	(HW) 3.44	0	5.61	4.92	-0.69	5.08	-0.53	5.88	5.04	-0.84	4.91	-0.97
		484	5.73	4.83	-0.90	4.93	-0.80	--	--	--	--	--
		968	5.76	4.85	-0.91	4.88	-0.88	6.23	5.16	-1.07	4.98	-1.25

TABLE XXI. TOTAL Ca IN ALL LEACHATE AND PLANT TOPS AND EXCHANGEABLE Ca IN LEACHED SOIL (MG/POT, MEANS OF 3 REPLICATES). DATA IN PARENTHESIS ARE PERCENT OF TOTAL (APPLIED + EXCHANGEABLE OR EXTRACTABLE)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)			
			Leachate	Plant	Soil	Total
Waimea	(LW) 0.86	0	896.21 (14.00)	14.32 (0.20)	5,200.00 (81.70)	6,110.53 (95.90)
		484	525.61 (8.26)	15.81 (0.24)	5,200.00 (81.76)	5,741.42 (90.26)
		968	262.41 (4.12	20.81 (0.32)	4,967.00 (78.09)	5,250.22 (82.53)
	(HW) 3.44	0	1,341.21 (21.08)	8.86 (0.13)	4,767.00 (74.95)	6,117.07 (96.16)
		484	972.70 (15.29)	9.36 (0.14)	4,800.00 (75.47)	5,782.06 (90.90)
		968	490.57 (7.71)	9.35 (0.14)	4,933.00 (77.56)	5,432.92 (85.41)
Halii	(LW) 0.86	0	627.07 (20.18)	1.90 (0.06)	1,273.00 (40.98)	1,901.97 (61.22)
		484	474.65 (15.28)	1.65 (0.05)	1,187.00 (38.21)	1,663.30 (55.55)
		968	231.01 (7.43)	2.14 (0.06)	1,087.00 (34.99)	1,320.15 (42.48)
	(HW) 3.44	0	1,218.01 (39.21)	1.55 (0.04)	773.00 (24.88)	1,992.56 (64.13)
		484	877.56 (28.25)	1.50 (0.04)	800.00 (25.75)	1,679.06 (54.04)
		968	466.80 (15.02)	1.74 (0.05)	833.00 (26.81)	1,301.54 (41.88)

TABLE XXI. TOTAL Ca IN ALL LEACHATE AND PLANT TOPS AND EXCHANGEABLE Ca IN LEACHED SOIL (MG/POT, MEANS OF 3 REPLICATES). DATA IN PARENTHESIS ARE PERCENT OF TOTAL (APPLIED + EXCHANGEABLE OR EXTRACTABLE) (Continued)

Soil	cm H_2O per application	ppm Si	P-750 ppm (HP)			
			Leachate	Plant	Soil	Total
Waimea	(LW) 0.86	0	626.20 (9.80)	45.82 (0.70)	5,367.00 (84.30)	6,039.02 (94.80)
		484	--	--	--	--
		968	162.53 (2.55)	42.90 (0.67)	4,933.00 (77.56)	5,138.43 (80.78)
	(HW) 3.44	0	1,009.01 (15.86)	14.76 (0.23)	5,033.00 (79.13)	6,056.77 (95.22)
		484	--	--	--	--
		968	429.58 (6.75)	13.92 (0.21)	4,900.00 (77.04)	5,343.00 (84.00)
Halii	(LW) 0.86	0	273.78 (8.81)	25.36 (0.81)	1,280.00 (41.21)	1,579.14 (50.83)
		484	--	--	--	--
		968	92.11 (2.96)	25.57 (0.82)	1,180.00 (37.99)	1,297.67 (41.77)
	(HW) 3.44	0	656.09 (21.12)	24.61 (0.79)	1,000.00 (32.19)	1,680.70 (54.10)
		484	--	--	--	--
		968	219.79 (7.07)	26.45 (0.85)	1,060.00 (34.12)	1,306.24 (42.04)

TABLE XXII. TOTAL K IN ALL LEACHATES AND PLANT TOPS AND EXCHANGEABLE K IN LEACHED SOIL (MG/POT, MEANS OF 3 REPLICATES). DATA IN PARENTHESIS ARE PERCENT OF TOTAL (APPLIED + EXCHANGEABLE OR EXTRACTABLE)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)			
			Leachate	Plant	Soil	Total
Waimea	(LW) 0.86	0	88.45 (4.11)	62.59 (2.91)	1,800.00 (83.72)	1,953.04 (90.83)
		484	69.48 (3.23)	78.80 (3.66)	1,800.00 (83.72)	198.48 (90.61)
		968	52.45 (2.43)	127.08 (5.91)	1,767.00 (82.18)	1,946.53 (90.52)
	(HW) 3.44	0	198.88 (9.25)	73.64 (3.42)	1,733.00 (80.60)	2,005.52 (93.27)
		484	163.75 (7.61)	79.26 (3.68)	1,767.00 (82.18)	2,010.01 (93.47)
		968	131.39 (6.11)	82.77 (3.84)	1,767.00 (82.18)	1,981.16 (92.13)
Halii	(LW) 0.86	0	36.90 (12.77)	4.10 (1.32)	240.00 (77.41)	283.70 (91.50)
		484	37.83 (12.20)	2.38 (0.76)	253.00 (81.61)	293.21 (94.57)
		968	30.02 (9.68)	5.36 (1.72)	247.00 (79.67)	282.38 (91.07)
	(HW) 3.44	0	201.27 (64.92)	4.34 (1.40)	87.00 (28.06)	292.61 (94.38)
		484	190.29 (61.38)	5.28 (1.70)	107.00 (34.51)	302.57 (97.59)
		968	156.90 (50.61)	5.47 (1.76)	107.00 (34.51)	269.37 (86.88)

TABLE XXII. TOTAL K IN ALL LEACHATES AND PLANT TOPS AND EXCHANGEABLE K IN LEACHED SOIL (MG/POT, MEANS OF 3 REPLICATES). DATA IN PARENTHESIS ARE PERCENT OF TOTAL (APPLIED + EXCHANGEABLE OR EXTRACTABLE) (Continued)

Soil	cm H_2O per application	ppm Si	P-750 ppm (HP)			
			Leachate	Plant	Soil	Total
Waimea	(LW) 0.86	0	72.10 (3.35)	268.27 (12.47)	1,700.00 (79.06)	2,040.37 (94.88)
		484	--	--	--	--
		968	40.18 (1.68)	344.74 (16.03)	1,700.00 (79.06)	2,084.92 (96.95)
	(HW) 3.44	0	168.24 (7.82)	115.60 (5.37)	1,700.00 (79.06)	1,983.84 (92.25)
		484	--	--	--	--
		968	126.47 (5.88)	124.23 (5.77)	1,767.00 (82.18)	2,017.70 (93.83)
Halii	(LW) 0.86	0	36.69 (11.83)	150.03 (48.39)	93.00 (30.00)	279.72 (90.22)
		484	--	--	--	--
		968	26.67 (8.60)	158.47 (51.11)	87.00 (28.06)	292.61 (94.38)
	(HW) 3.44	0	126.01 (40.64)	104.35 (33.66)	47.00 (15.16)	277.36 (89.46)
		484	--	--	--	--
		968	85.12 (27.45)	162.82 (52.52)	47.00 (15.16)	294.94 (95.13)

TABLE XXIII. TOTAL Mg IN ALL LEACHATES AND PLANT TOPS AND EXCHANGEABLE Mg IN LEACHED SOIL (MG/POT, MEANS OF 3 REPLICATES). DATA IN PARENTHESIS ARE PERCENT OF TOTAL (APPLIED + EXCHANGEABLE OR EXTRACTABLE)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)			
			Leachate	Plant	Soil	Total
Waimea	(LW) 0.86	0	226.50 (20.40)	7.41 (0.60)	903.00 (81.49)	1,136.91 (102.49)
		484	161.51 (14.57)	8.49 (0.76)	980.00 (88.44)	1,150.00 (103.77)
		968	91.00 (8.21)	14.00 (1.26)	1,033.00 (93.23)	1,138.00 (102.70)
	(HW) 3.44	0	375.39 (33.87)	4.09 (0.36)	790.00 (71.29)	1,169.48 (105.52)
		484	282.29 (25.47)	4.40 (0.39)	880.00 (79.42)	1,166.69 (105.28)
		968	167.11 (15.08)	4.97 (0.44)	990.00 (89.35)	1,162.08 (104.87)
Halii	(LW) 0.86	0	43.84 (33.72)	0.61 (0.46)	85.00 (65.38)	129.45 (99.56)
		484	41.28 (31.75)	0.56 (0.43)	95.00 (73.07)	136.84 (105.25)
		968	26.05 (20.03)	0.83 (0.63)	105.00 (80.76)	131.88 (101.42)
	(HW) 3.44	0	100.87 (77.59)	0.60 (0.46)	46.00 (35.38)	147.47 (113.43)
		484	85.54 (65.80)	0.57 (0.43)	60.00 (46.15)	146.11 (112.38)
		968	60.24 (46.33)	0.69 (0.53)	66.00 (50.76)	126.93 (97.62)

TABLE XXIII. TOTAL Mg IN ALL LEACHATES AND PLANT TOPS AND EXCHANGEABLE Mg IN LEACHED SOIL (MG/POT, MEANS OF 3 REPLICATES). DATA IN PARENTHESIS ARE PERCENT OF TOTAL (APPLIED + EXCHANGEABLE OR EXTRACTABLE) (Continued)

Soil	cm H_2O per application	ppm Si	P-750 ppm (HP)			
			Leachate	Plant	Soil	Total
Waimea	(LW) 0.86	0	180.93 (16.32)	32.86 (2.96)	913.00 (82.40)	1,126.79 (101.68)
		484	--	--	--	--
		968	54.75 (4.94)	39.14 (3.53)	1,043.00 (94.13)	1,136.89 (102.60)
	(HW) 3.44	0	289.77 (26.15)	7.56 (0.68)	847.00 (76.44)	1,144.33 (103.27)
		484	--	--	--	--
		968	156.54 (14.12)	8.30 (0.74)	1,000.00 (90.25)	1,164.84 (105.11)
Halii	(LW) 0.86	0	29.40 (22.61)	13.12 (10.09)	83.00 (63.84)	125.52 (96.54)
		484	--	--	--	--
		968	11.93 (9.17)	17.12 (13.16)	101.00 (77.69)	130.05 (100.02)
	(HW) 3.44	0	63.81 (52.93)	13.75 (10.57)	55.00 (42.30)	137.56 (105.80)
		484	--	--	--	--
		968	32.13 (24.71)	17.40 (13.38)	85.00 (65.38)	134.53 (103.47)

TABLE XXIV. TOTAL Na IN ALL LEACHATES AND PLANT TOPS AND EXCHANGEABLE Na IN LEACHED SOIL (MG/POT, MEANS OF 3 REPLICATES). DATA IN PARENTHESIS ARE PERCENT OF TOTAL (APPLIED + EXCHANGEABLE OR EXTRACTABLE)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)			
			Leachate	Plant	Soil	Total
Waimea	(LW) 0.86	0	37.31 (39.69)	0.20 (0.21)	82.00 (87.23)	119.51 (127.13)
		484	35.00 (33.98)	0.25 (0.24)	92.00 (89.32)	127.25 (123.54)
		968	31.22 (27.87)	0.41 (0.36)	102.00 (91.07)	133.63 (119.30)
	(HW) 3.44	0	77.25 (82.18)	0.22 (0.23)	46.00 (48.93)	123.47 (131.34)
		484	75.86 (73.65)	0.26 (0.25)	52.00 (50.48)	128.12 (124.38)
		968	67.17 (59.97)	0.27 (0.24)	68.00 (60.71)	135.44 (120.92)
Halii	(LW) 0.86	0	14.32 (51.14)	0.05 (0.17)	13.00 (46.42)	27.37 (97.73)
		484	19.12 (51.67)	0.05 (0.13)	18.00 (48.64)	37.17 (100.44)
		968	20.63 (44.84)	0.06 (0.13)	24.00 (52.17)	44.69 (97.14)
	(HW) 3.44	0	27.85 (99.46)	0.04 (0.14)	6.00 (21.42)	33.89 (121.02)
		484	34.13 (92.24)	0.04 (0.10)	6.00 (16.21)	40.17 (108.55)
		968	42.26 (91.96)	0.05 (0.10)	5.00 (10.86)	47.31 (102.82)

TABLE XXIV. TOTAL Na IN ALL LEACHATES AND PLANT TOPS AND EXCHANGEABLE Na IN LEACHED SOIL (MG/POT, MEANS OF 3 REPLICATES). DATA IN PARENTHESIS ARE PERCENT OF TOTAL (APPLIED + EXCHANGEABLE OR EXTRACTABLE) (Continued)

Soil	cm H_2O per application	ppm Si	P-750 ppm (HP)			
			Leachate	Plant	Soil	Total
Waimea	(LW) 0.86	0	36.96 (39.31)	0.66 (0.70)	82.00 (87.23)	119.62 (127.24)
		484	--	--	--	--
		968	24.30 (21.69)	0.84 (0.75)	104.00 (92.85)	129.14 (115.29)
	(HW) 3.44	0	71.03 (75.56)	0.35 (0.37)	54.00 (57.44)	125.38 (133.37)
		484	--	--	--	--
		968	68.41 (61.08)	0.38 (0.33)	72.00 (64.28)	140.79 (125.69)
Halii	(LW) 0.86	0	11.47 (40.96)	0.38 (1.35)	13.00 (46.42)	24.85 (88.73)
		484	--	--	--	--
		968	12.93 (28.10)	0.48 (1.04)	27.00 (58.09)	40.41 (87.83)
	(HW) 3.44	0	25.64 (91.57)	0.55 (1.96)	9.00 (32.14)	35.19 (125.67)
		484	--	--	--	--
		968	35.13 (76.36)	0.60 (1.30)	10.00 (21.73)	45.73 (99.39)

TABLE XXV. TOTAL P IN ALL LEACHATES AND PLANT TOPS AND EXTRACTABLE P IN LEACHED SOIL (MG/POT, MEANS OF 3 REPLICATES). DATA IN PARENTHESIS ARE PERCENT OF TOTAL (APPLIED + EXCHANGEABLE OR EXTRACTABLE)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)			
			Leachate	Plant	Soil	Total
Waimea	(LW) 0.86	0	10 (0.003)	4,180 (1.09)	310,000 (81.15)	314,200 (82.25)
		484	22 (0.006)	3,990 (1.04)	338,000 (88.48)	342,012 (89.53)
		968	38 (0.009)	6,630 (1.74)	344,000 (90.05)	350,668 (91.80)
	(HW) 3.44	0	121 (0.03)	5,010 (1.31)	342,000 (89.53)	347,131 (90.87)
		484	153 (0.04)	5,430 (1.42)	344,000 (90.05)	349,583 (91.51)
		968	258 (0.07)	6,110 (1.59)	345,000 (90.31)	351,368 (91.97)
Halii	(LW) 0.86	0	5 (0.005)	190 (0.19)	11,000 (10.89)	11,195 (11.09)
		484	6 (0.006)	190 (0.19)	12,000 (11.88)	12,196 (12.07)
		968	10 (0.01)	260 (0.26)	11,000 (10.89)	11,270 (11.16)
	(HW) 3.44	0	16 (0.02)	160 (0.16)	10,000 (9.90)	10,176 (10.08)
		484	15 (0.02)	230 (0.23)	11,000 (10.89)	11,245 (11.13)
		968	19 (0.02)	240 (0.24)	11,000 (10.89)	11,259 (11.15)

TABLE XXV. TOTAL P IN ALL LEACHATES AND PLANT TOPS AND EXTRACTABLE P IN LEACHED SOIL (MG/POT, MEANS OF 3 REPLICATES). DATA IN PARENTHESIS ARE PERCENT OF TOTAL (APPLIED + EXCHANGEABLE OR EXTRACTABLE) (Continued)

Soil	cm H_2O per application	ppm Si	P-750 ppm (HP)			
			Leachate	Plant	Soil	Total
Waimea	(LW) 0.86	0	222 (0.02)	32,190 (3.12)	558,000 (54.07)	590,412 (57.21)
		484	--	--	--	--
		968	360 (0.04)	35,850 (3.47)	600,000 (58.14)	636,210 (61.65)
	(HW) 3.44	0	2,265 (0.22)	12,180 (1.18)	604,000 (58.53)	618,445 (59.93)
		484	--	--	--	--
		968	3,375 (0.33)	13,170 (1.28)	608,000 (58.91)	624,545 (60.52)
Halii	(LW) 0.86	0	71 (0.009)	6,350 (0.85)	184,000 (24.50)	196,842 (25.98)
		484	--	--	--	--
		968	74 (0.009)	7,250 (0.97)	170,000 (22.64)	201,648 (26.85)
	(HW) 3.44	0	221 (0.03)	8,550 (1.14)	168,000 (22.37)	176,771 (23.54)
		484	--	--	--	--
		968	253 (0.03)	10,607 (1.42)	149,000 (19.84)	159,923 (21.29)

TABLE XXVI. TOTAL Si IN ALL LEACHATES AND PLANT TOPS AND EXTRACTABLE Si IN LEACHED SOIL (MG/POT, MEANS OF 3 REPLICATES). DATA IN PARENTHESIS ARE PERCENT OF TOTAL (APPLIED + EXCHANGEABLE OR EXTRACTABLE)

Soil	cm H_2O per application	ppm Si	P-100 ppm (LP)			
			Leachate	Plant	Soil	Total
Waimea	(LW) 0.86	0	7.59 (0.63)	32.63 (2.71)	1,123.00 (93.42)	1,163.22 (96.76)
		484	8.82 (0.52)	45.74 (2.71)	1,284.00 (76.15)	1,338.56 (79.38)
		968	9.55 (0.44)	60.74 (2.79)	1,364.00 (62.85)	1,434.29 (66.08)
	(HW) 3.44	0	34.01 (2.82)	53.75 (4.47)	1,207.00 (100.41)	1,294.76 (107.70)
		484	41.02 (2.43)	61.97 (3.67)	1,263.00 (74.91)	1,365.99 (81.01)
		968	48.27 (2.22)	69.57 (3.20)	1,377.00 (63.45)	1,494.84 (68.87)
Halii	(LW) 0.86	0	0.88 (3.03)	1.09 (3.75)	31.00 (106.89)	32.97 (113.67)
		484	4.12 (0.80)	2.69 (0.52)	107.00 (20.85)	113.81 (22.17)
		968	6.83 (0.68)	5.80 (0.58)	144.00 (14.44)	156.63 (15.70)
	(HW) 3.44	0	2.99 (10.31)	0.64 (2.20)	33.00 (113.79)	36.63 (126.30)
		484	16.20 (3.15)	3.50 (0.68)	108.00 (21.05)	127.70 (24.88)
		968	29.15 (2.92)	5.34 (0.53)	153.00 (15.34)	187.49 (18.79)

TABLE XXVI. TOTAL Si IN ALL LEACHATES AND PLANT TOPS AND EXTRACTABLE Si IN LEACHED SOIL (MG/POT, MEANS OF 3 REPLICATES). DATA IN PARENTHESIS ARE PERCENT OF TOTAL (APPLIED + EXCHANGEABLE OR EXTRACTABLE) (Continued)

Soil	cm H_2O per application	ppm Si	P-750 ppm (HP)			
			Leachate	Plant	Soil	Total
Waimea	(LW) 0.86	0	8.31 (0.69)	123.96 (10.31)	1,167.00 (97.08)	1,303.08 (108.39)
		484	--	--	--	--
		968	10.17 (0.46)	175.16 (8.07)	1,235.00 (56.91)	1,420.33 (65.44)
	(HW) 3.44	0	40.56 (3.37)	85.45 (7.10)	1,179.00 (98.08)	1,305.01 (108.55)
		484	--	--	--	--
		968	56.00 (2.58)	105.48 (4.86)	1,242.00 (57.23)	1,403.48 (63.67)
Halii	(LW) 0.86	0	1.41 (4.86)	8.52 (29.37)	28.00 (96.55)	37.93 (130.78)
		484	--	--	--	--
		968	4.72 (0.47)	34.65 (3.47)	84.00 (8.42)	123.37 (12.36)
	(HW) 3.44	0	4.26 (14.68)	14.62 (50.41)	24.00 (82.75)	48.88 (147.84)
		484	--	--	--	--
		968	21.73 (2.17)	62.69 (6.28)	78.00 (7.82)	162.42 (16.27)

Methods of Analysis

1. Leachate analysis

(a) Calcium and magnesium

Calcium and magnesium in leachates were determined on a Perkin-Elmer Model 303 atomic absorption sprectrophotometer at wave length 422.7 mu and 285.2 mu respectively. For calcium, 0.1% lanthanum oxide was added to reduce interferences.

(b) Potassium and sodium

Potassium and sodium in leachates were determined on a Beckman model DU flame sprectrophotometer at wave length 767 mu and 589 mu respectively.

(c) Phosphorus

The chlorostannous reduced molybdophosphoric blue color method, in sulfuric acid system was used to determine phosphorus (Jackson, 1958).

(d) Silicon

Silicon determination was based on the reaction of dissolved silicon and molybdate in sulfuric acid to form yellow silicomolybdate complex which is subsequently reduced to molybdenum blue (Kilmer, 1965) and read at 660 mu.

2. Plant analysis

(a) Nitric-perchloric acid digestion

Digestion of plant samples was done with 15 ml 2:1 nitric-perchloric acid mixture in 100 ml Kjeldahl

flask (Jackson, 1958). The sample was allowed to stand overnight and then digested at low temperature for 20 minutes. Digestion was carried out until white fumes appeared. To complete the dehydration of silicon, it was continued for another 15 minutes. The solution sample was made to volume with distilled water.

(b) Calcium, potassium, magnesium and sodium

Plant calcium, potassium, magnesium and sodium were determined using the same methods as in the leachates. Plant phosphorus was determined using the vanadate-molybdate yellow method of Barton (1948).

(c) Lithium tetraborate fusion

A modified method of Sur and Ingamells (1966) was used. The dried plant samples were ashed in platinum crucible at 550°C. Ash was mixed with 0.5 gm lithium tetraborate and transfered to carbon crucible and fused at 950°C in a muffled furnace for 15 minutes. The crucible was swirled to coalesce the melt, and the contents were poured into 100 ml of 0.5N nitric acid. The mixture was stirred with a magnetic stirrer until complete solution was obtained. The method for silicon determination was the same as for silicon of leachates.

3. Soil analysis

(a) Cation exchange capacity

To 25 gm (oven dry equivalent) of each soil sample,

200 ml of N-NH_4OAc at pH 7 was added and left overnight. During this period, the soil was shaken three times for 15 minutes. Filtration was carried out using Whatman No. 42 filter paper in a Buchner funnel. Another 200 ml of N-NH_4OAc was used to wash the soil for complete saturation of ammonium ions on the exchange complex. Filtrate plus washings were saved for exchangeable cation determinations. Soil residue was washed with 200 ml of methyl alcohol. The washed soil and filter paper were transfered to an Erlenmeyer flask. To this, 200 ml of 4% KCl was added and shaken for 30 minutes. The soil was again filtered and washed with another 200 ml KCl. Filtrate plus washings were transfered to 800 ml Kjeldahl flask. A few pieces of mossy zinc and 10 ml 1:1 NaOH were added. The solution was distilled into 50 ml of 2% boric acid mixed indicator (methylene blue and methyl red) until two-thirds of the contents had distilled. The distillate was titrated with standard sulfuric acid.

Exchangeable calcium, potassium, magnesium and sodium in NH_4OAc were determined using the same methods for those of leachates.

(b) Phosphorus and silicon

Soil phosphorus and silicon were extracted using modified Truog solution (0.02 N-H_2SO_4 + 3 gm NH_4SO_4

per liter). Two grams (oven dry equivalent) of soil were shaken in 200 ml of Truog solution for 30 minutes. After filtration, phosphorus and silicon were determined in the same way as for the leachate.

(c) Total nitrogen

Total nitrogen was determined using the regular macro-Kjeldahl method of Bremner (1965).

(d) Organic carbon

Organic carbon was determined using Wakely-Black method (Allison, 1965).